Salmonella enterica in Swine Feed Ingredients:

A Review and Implications for Control Policies

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The aim of this licentiate thesis in veterinary medicine is to examine data from previous research to establish whether there is a greater risk of occurrence of *Salmonella* in certain feed ingredients, whether sufficient data is available to link specific serovars of *Salmonella* with specific feed ingredients, and to evaluate the significance of these results for *Salmonella* control policies. The thesis begins with a literature review of current knowledge of *Salmonella* epidemiology, the feed industry, and control policy. The second part of the thesis will contain tables from a database of research figures on *Salmonella* in feed ingredients from 38 studies and governmental zoonosis programs. A discussion follows, outlining the significance of these results for the *Salmonella* serovar-specific post-harvest and zoonotic pre-harvest approaches to the control of *Salmonella* in feeds in the United States of America and Finland, respectively. The results can inform further research by mapping out to what degree *Salmonella* in feed ingredients has been investigated, aid in policy formation, and direct testing and management at feed mills.

Analysis of the database indicates that *Salmonella* is common in feed ingredients, and that prevalence and serovars vary between ingredients and geographic regions. Rendered products tend to have the highest prevalence of *Salmonella* in countries that do not implement pre-harvest *Salmonella* control programs. Out of animal-derived products, blood and milk by-products may be least prone to contamination. Of plant-derived feed ingredients, oilseeds are more frequently contaminated than cereal grains, but cereal grains are frequently contaminated by the serovar *S.* Typhimurium. Although connections could not be made between specific feed ingredients and specific *Salmonella* serovars due to the scarcity of sample data, several possible oilseed-associated, grain-associated, and general-type serovars were identified. Serovars that cause salmonellosis in humans exist in swine feeds. *Salmonella* Cholerasuis was not isolated from animal feeds ingredients.

The recently issued United States Food and Drug Administration compliance policy guide Sec. 690.800 does not address broad-host type *Salmonella* serovars in animal feeds. In light of the results, at least *Salmonella* Typhimurium should be on the list of *Salmonella* serovars that pose a risk for animal and human health in swine feed.

For Finland and other countries that have already invested significantly in pre-harvest feed safety, there is no great benefit to converting to serovar-specific models of risk assessment at this juncture, when it has not been confirmed that certain *Salmonella* serovars harbored in feeds do not cause illness in swine and humans.

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Salmonella enterica, swine feed ingredients, *Salmonella* control, *Salmonella* surveillance

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Tiivistelmä - - Referat – Abstract

Tämän lisensiaatin tutkielman tarkoituksena oli laatia kirjallisuuskatsaus *Salmonella enterica* -bakteerin prevalenssista ja serotyyppien esiintymisestä sianrehujen ainesosissa ja pohtia näiden merkitystä salmonellavalvonnalle.

Yhdysvalloissa siirryttiin vuonna 2013 serotyyppikohtaiseen valvontaan rehujen ainesosissa, kun taas Suomen kansallinen salmonellavalvontaohjelma tukeutuu olettamukseen, että kaikki salmonellan serotyypit ovat zoonoottisia. USA:ssa rehuille ei suoriteta rutiininomaista kuumennuskäsittelyä. Mikäli jotkut serotyypit tai erityisen paljon salmonellaa esiintyisi vain tietyissä rehujen ainesosissa, voitaisiin näiden ainesosien käyttöä välttää sianrehuissa tai ohjata kyseinen ainesosa dekontaminaatiokäsittelyyn. Tutkielman löydöksiä voidaan hyödyntää jatkotutkimusten suunnittelussa ja tukemaan salmonellavalvontaan liittyvää päätöksentekoa.

Kirjallisuuskatsauksen ensimmäinen osa esittelee *Salmonella enterican* ekologiaa ja epidemiologiaa erityisesti sianrehuihin liittyen. Myös rehuntuotantoa ja valvontaa käydään läpi, Yhdysvaltojen ja Suomen toimiessa esimerkkeinä erityyppisistä valvontaohjelmista. Toisen osan tarkoitus on esitellä ja analysoida ainesosakohtaisia tuloksia tutkielmaa varten kootusta 38 tutkimusta ja valtion zoonoosiohjelmaa käsittävästä tietokannasta. Diskussio-osiossa pohditaan tulosten merkitystä Yhdysvaltojen ja Suomen salmonellavalvonnalle.

Salmonellaa esiintyy yleisesti sianrehujen ainesosissa, mutta sekä prevalenssi että serotyypit vaihtelevat ainesosittain ja maantieteellisen sijainnin mukaan. Eläinperäisissä sivutuotteissa oli korkein prevalenssi maissa, joilla ei ole kansallista salmonellavalvontaohjelmaa. Eläinperäisistä tuotteista veri ja maito olivat vähiten saastuneita. Kasviperäisistä rehuaineista öljykasvit olivat enemmän saastuneita, kuin vilja, mutta viljaa saastuttaa usein siolle ja ihmisille virulentti serotyyppi *S.* Typhimurium. Vaikka yksittäisiä rehuaineita ei voitu yhdistää tiettyihin *Salmonella*-serotyyppeihin pienistä näytemääristä johtuen, useita serotyyppejä havaittiin, jotka saattavat olla yhteyksissä öljykasveihin tai viljoihin, tai jotka esiintyvät monissa rehutyypeissä. Ihmisille usein salmonelloosia aiheuttavia serotyyppejä eristettiin myös sianrehujen ainesosista. Sialle yleisinfektiota aiheuttavaa *Salmonella* Cholerasuista ei eristetty rehujen ainesosista.

Hiljattain Yhdysvaltain elintarvike- ja lääkevirasto FDA on kieltänyt eläimille yleisinfektiota aiheuttavien *Salmonella*-serotyyppien esiintymisen rehuissa, joka sianrehuissa merkitsee *S.* Cholerasuista, sallien muiden serotyyppien esiintymisen rehuissa. Mikäli tämän tutkielman tavoin todetaan, ettei *S.* Cholerasuis saastuta rehuja, sianrehujen salmonellavalvonnasta uhkaa tulla olematonta. Lisäksi ainakin *S.* Typhimurium pitäisi olla kiellettyjen *Salmonella*-serotyyppien luettelossa, sillä sitä esiintyy usein sianrehun ainesosissa ja se aiheuttaa vaaraa ihmisten ja eläinten terveydelle. Maat, joissa on jo käynnissä kansallinen salmonellavalvontaohjelma, ovat tehneet merkittäviä investointeja hävittääkseen salmonellan myös sikatiloilta ja rehuntuotannosta. Näille maille ei ole suurta hyötyä siirtymisestä serotyyppikohtaiseen riskinarviointiin, ennen kuin on tieteellisesti vahvistettu, että tietyt rehuissa esiintyvät *Salmonella*-serotyypit eivät aiheuta salmonelloosia sioissa ja ihmisissä.

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1 INTRODUCTION

Risk assessments that justify pre-harvest control programs, such as the Finnish National Salmonella Control Program, are based on the assumption that *Salmonella enterica* can be passed on through animal feed to swine and then to humans. Risk assessments in pre-harvest *Salmonella* control programs do not take into account differences in the epidemiology of *Salmonella* serovars, but are grounded in the premise that all *Salmonella* serovars have zoonotic potential. The United States has taken a serovar-specific approach to risk assessment. In 2013, the Unites States Food and Drug Administration (US FDA) issued a new Compliance Policy Guide (CPG) stating that if specific host-specific serovars of *Salmonella enterica* are detected in feed, namely serovars that have an impact on animal health, the feed must be detained or decontaminated with a pre-approved treatment method. The FDA simultaneously revoked a zero-tolerance policy for animal feeds contaminated with *Salmonella*. (FDA 2013) The reason for this change in policy is a change in understanding of the epidemiology of Salmonella: that *Salmonella* serovars have different ecologies and differing abilities to infect animals and humans, which merit serovar-specific risk assessments. The abilities of *Salmonella* serovars to survive in feed ingredients and infect humans and animals are topics of ongoing investigation.

My thesis begins with a literature review that concentrates on current knowledge of *Salmonella* epidemiology, control, and policy. The need for an investigation of *Salmonella* prevalence and serovars in swine feed ingredients will be contextualized within operation of the US feed industry, as well as current *Salmonella* surveillance and control programs in the USA and Finland. These programs serve as models of pre- and post-harvest control strategies.

Next, I present tables from a database I have assembled that includes research results on *Salmonella* prevalence and *Salmonella* serovars in feed ingredients. I will identify the limitations of current scientific knowledge on *Salmonella* in specific feed ingredients and where further investigation is needed. Finally, I discuss the

implications of the results of this literature review and feed ingredient and *Salmonella* serovar-specific information on the US and Finnish *Salmonella* control programs.

The hypothesis is that the prevalence of *Salmonella* in feed ingredients will vary, and that certain feed ingredients will be better suited to sustain certain serovars of *Salmonella*.

The results of this thesis may be applied to direct further research by mapping out to what degree *Salmonella* in feed ingredients have been investigated. Information on prevalence and serovars in feed ingredients may aid in policy formation and have applications to risk management systems at feed mills and farms. Risk-based testing could be carried out at the earliest step in the feed-to-food chain, thus bringing down costs and maximizing the possibility to detect *Salmonella* in feed. High-risk feed ingredients could either be treated or left out of swine feed.

2 LITERATURE REVIEW

2.1 *Salmonella enterica* Organisms

2.1.1 Classification and Characteristics of *Salmonella enterica*

Salmonella is a genus of gram-negative, rod-shaped, motile, non-spore-forming, facultatively anaerobic, chemo-organotrophic enterobacteria with peritrichous flagella. (Bell and Kyriakides 2002) There is great genetic variation within *Salmonella*. All the disease-causing microbes of the *Salmonella* genus are of the *Salmonella enterica* subspecies *enterica*. Serovars are classified according to their somatic (O) and flagellar (H) antigens. Roughly 2500 serovars of *Salmonella enterica* have been identified. In nomenclature, serovars, i.e. serotypes of *Salmonella enterica subspecies enterica*, are generally referred to as separate species. For example, *S.enterica* subsp. *enterica* serovar Typhimurium is commonly referred to as *Salmonella* Typhimurium. (Anonymous, 2007)

Salmonella multiply at 7 – 45 °C, with highest rates of growth measured at

intestinal temperatures (37 °C). *Salmonella* also survive freezing and desiccation. It has an A_w min of 0.94 and can stand a salt concentration of 5%. It grows at a pH of 4.5–9.5, the optimum being 6.5–7.5. Survival is shortened below a pH of 5.0, and the bacteria are inactived by heat and sunlight. Disinfectants that are chlorine and iodine-based are efficient against *Salmonella*. (Bell and Kyriakides 2002)

2.1.2 Human Salmonellosis

Salmonella is one of the most important causes of bacterial gastroenteritis worldwide, causing an estimated 80.3 million cases of foodborne illness and 155,000 deaths annually. (Majowicz et al. 2010) *Salmonella* continues to be a significant cause of illness both in developed and developing countries, in children and in the general adult population. (Ibid.) In the United States in 1996–1999, the Foodborne Illness Active Surveillance Network (Foodnet) estimated that there were 1.4 million infections in the United States that resulted in 168,000 visits to a physician. (Voetsch et al. 2004) Annually, 15,000 hospitalizations and 400 deaths were attributed to *Salmonella*. (Ibid.) Because of underreporting, laboratory-based surveillance data underestimates the burden of disease. (Flint et al. 2005)

The US Centers for Disease Control (CDC) has published a recent estimate of foodborne illness that indicated that approximately one million cases of human non-typhoid salmonellosis occurred annually in the United States in the years 2000–2008. (Scallan et al. 2011) *Salmonella* is the main bacterial cause of foodborne illness, causing 11% of all foodborne illness. It was the leading cause of hospitalization (35%) and death (28%) of all deaths due to acute gastroenteritis. (Scallan et al. 2011) However, a recent mathematical model based on surveillance data from the CDC and *Salmonella* surveillance data from United States Department of Agriculture Animal and Plant Health Inspection Service (APHIS) suggests that across 105 serovars, sporadic cases of *Salmonella* infection at the point of processing is only attributable to pork in less than <1% of cases. (Guo et al. 2011)

Salmonella gastroenteritis is self-limiting in healthy adults, but 10–15% of the population, the young, old, pregnant and immunodeficient can be prone to systemic

spread of the bacteria that requires treatment with antibiotics. Antimicrobial resistance has increased significantly in pork-related *Salmonella* serovars such as *Salmonella* Typhimurium and *Salmonella* Derby. *Salmonella* Typhimurium strains of the phage types DT104, DT120, and DT193 have all being linked to swine and are multiresistant to 4–10 antimicrobial agents. (Boyen et al. 2008)

2.1.3 Reservoirs of *Salmonella enterica*

The reservoir of *Salmonella enterica* is the intestinal tract of warm- and cold-blooded animals. The most common transmission route is the feco-oral route, but *Salmonella* may also be transmitted directly through oropharyngeal secretions. *Salmonellae* are zoonotic and can infect a broad range of hosts, although species-specificity between serovars varies greatly.

Salmonella serovars have recently been classified according to species specificity. (Uzzau et al. 2000) **Species-specific** *Salmonella enterica* serovars cause a generalized, typhoid-like disease in its host species, such as *Salmonella* Typhi in humans. **Host-specific** *Salmonella enterica* serovars cause a typhoid-like disease in the animal for which it is species-specific, and gastroenteritis in other animals, such as *Salmonella* Cholerasuis in swine. Another example of this type of *Salmonella* serovar is *S*. Typhimurium, which causes gastroenteritis in swine and humans and a generalized infection in mice. The majority of *Salmonella* serovars are of the zoonotic, **broad-host** type. They are able to colonize the alimentary tract of different animals but rarely cause systemic infections. An example of a broad-host type *Salmonella* serovar is *Salmonella* Derby. (Uzzau et al. 2000)

Salmonellae can also colonize animals without causing clinical disease. The ubiquitous nature of *Salmonella* can be attributed to reservoirs of long-term asymptomatic carriers that shed *Salmonella* intermittently in fecal matter, its broad zoonotic potential, as well as its ability to persist in the environment. *Salmonella* can survive outside the intestinal tracts of hosts for significantly long periods of time. It can stay infective for years in suitable organic substrates, such as feces and feed, and

survive in water. It can also be transmitted via fomites such as boots and car tires. (Zimmerman 2012)

2.1.4 The Clinical Picture of Salmonellosis in Swine

The clinical picture of salmonellosis in swine varies. Non-typhoidal salmonellosis is either asymptomatic, or may manifest as intermittent gastroenteritis with bloody feces. The pathogenicity of *Salmonella* is based on its ability to invade the intestinal lining. In swine, asymptomatic serovars of *Salmonella* are carried in the tonsils, intestines and gut-associated lymphoid tissue. Non-typhoidal salmonellosis has not received as much research attention as typhoid salmonellosis. (Zimmerman 2012)

The serovars *S.* Cholerasuis and *S.* Typhisuis cause swine typhoid and a generalized infection, which is often fatal, with enterocolitis, septicemia and bacteremia. Locally, these serovars can cause lesions such as pneumonia, hepatitis, or meningitis, encephalitis and abortions. Of nontyphoidal *Salmonella* infections, *S.* Typhisuis may cause caseous lymphadenitis, and *S.* Typhimurium enterocolitis. (Zimmerman 2012)

2.1.5 *Salmonella* Serovar Epidemiology

Our current knowledge of the epidemiology of different *Salmonella* serovars is insufficient. It is well known that the virulence of infections in different animal species differs between serovars. In 2001, Sarwari et al. demonstrated that there is a significant mismatch between the serovar distribution of *Salmonella* serovars isolated from food animals and humans. Sarwari et al. (2001) proposed that the assumption that animal products are the primary source for human salmonellosis should be re-examined. Sarwari et al. (2001) concluded that the mismatch indicated that dose response and infectivity, as well as the ability for the serovar to cause a persistent infection, differ between serovars.

Others have called this claim into question. In their mathematical model, Sarwari et al. (2001) assumed that eating pork, poultry and beef would all have the

same risk. Li et al. (2011) noted that out of the 10 serovars most commonly associated with human infections, six are also found in the top serovars of swine and poultry. In addition, serovar prevalence also changes with time. For many years, Salmonellosis counts have stayed roughly the same in the US. When cases attributable to one serovar diminish, another takes its place. (Foley et al. 2008) Serovars Javiana and 4,[5],12:i:- are examples of emerging serotypes. (Ibid.)

Outbreak studies are the most straightforward way to attribute the source of cases of salmonellosis. Jackson et al. (2013) examined food commodities and serovars implicated in outbreaks during 1998–2008. The vehicle food products in outbreaks varied. Over 50% of outbreaks caused by serovars Mbandaka, Senftenberg, Javiana, Litchfield, Muenchen, and Poona were attributed to plant commodities. Serotypes Typhimurium and Newport were attributed to both animal and plant commodities. Serovars Enteritidis, Heidelberg and Hadar were attributed to eggs or poultry. (Jackson et al. 2013)

The more that is known about the epidemiology of *Salmonella enterica*, the more it becomes evident that the infectivity of broad-host type *Salmonella* serovars varies between mammalian species. Preference and adaptability for certain species and the ability to form persistent infections varies between serovars, and thus some serovars that are often isolated from feeds or from swine may be of low zoonotic importance to humans. (Davies et al. 2004) This would explain the discrepancy between the frequency of isolation of different serovars in feeds, food production animals, and humans. It stands to reason that the same could probably be true of the survival of different serovars of *Salmonella* on substrates in the environment would vary.

The same reasoning has been thought to apply to serovars infecting animals and serovars isolated from animal feeds. According to Davies, unlike the case of *Salmonella* Agona, it is more likely that there are many *Salmonella* serovars in feed that very rarely, if ever, cause infections in humans. (Davies et al. 2004) There are a few known cases of serovars that have low virulence in humans despite being common in animals. *Salmonella* Sofia, which belongs to *Salmonella enterica* subspecies *salamae*, is common in poultry in Australia, but rarely infects humans. (Duffy et al. 2012)

Similarly, avirulent serovars for humans seem to be *Salmonella* 4,12:d:–, in Germany and *S. enterica* Brancaster in Senegal. (Duffy et al. 2012)

Swedish experiences with *Salmonella* reflect that *Salmonella* Derby, a swine-associated serovar, was considerably more difficult to eradicate from a farm than a feed-borne outbreak of S. Cubana was from multiple farms. (Osterberg et al. 2010) This has suggested that feed-associated serovars may be less transmissible in herds than serovars associated with swine. Whether these observed differences are due to virulence factors or dose-response characteristics is unknown. (Osterberg et al. 2010) In an experimental study, Osterberg et al. (2010) compared differences in direct contact and indirect-contact transmissibility between feed associated serovars *S.* Cubana and *S.* Yoruba and swine-associated *S.* Derby and *S.* Typhimurium. Infectivity in all cases was low, but *S.* Typhimurium was isolated from three out of six swine at necropsy from the ileocecal node. (Osterberg et al. 2010)

Salmonella serovars may establish themselves in feed processing similarly to establishment in food processing plants. Serovar ability to persist and survive in dry environments and the ability to form biofilms are connected to their fitness for survival in the feed mill environment. *Salmonella* Agona and *S.* Montevideo are two examples of serovars with biofilm-forming abilities that are frequently isolated from feed mill environments. (Binter et al. 2011)

Certain serovars are known to be frequently isolated from animal feed ingredients, although much remains unknown. In the Finnish *Salmonella* control program, during 1995–2004, *S.* Senftenberg was isolated most often from sunflower seeds, and *S.* Tennessee and *S.* Mbandaka from crushed oil plant seeds and concentrates. In cereal grains and by-products, *S.* Livingstone was the most common isolate. (Huttunen et al. 2006)

The virulence factors of *Salmonella* serovars that cause major human illness are currently under intense investigation.

2.1.6 Virulent, Zoonotic Serovars

Salmonella Typhimurium is the most common *Salmonella* serovar isolated from humans currently in the US. (Foley et al. 2008) It is virulent in both swine and humans. For humans it has a higher mortality rate than other serovars, and the DT104 strain is multiresistant to antibiotics and complicates treatment. (Foley et al. 2008) The CDC publishes data on both clinical and non-clinical isolations of *Salmonella* from swine. *Salmonella* Typhimurium causes a disproportionately large amount of clinical illness in swine: 36% in 2005. (Foley et al. 2008)

S. Enteritidis is the most common serotype that causes human disease in the EU and is the second most common serotype in the US. It is mostly associated with poultry and can be directly transmitted inside eggs, unlike most other serotypes. *S.* Heidelberg is a similar, egg-invading serotype with higher pathogenicity for humans. (Jackson et al. 2013) Both *S.* Enteritidis and Heidelberg were isolated from some clinical cases in swine in the most recent data from the CDC. (2009 CDC)

S. Montevideo is associated with contaminated produce and poultry meat in human outbreak investigations. (Foley et al. 2008) *S.* Montevideo caused a few clinical (12) and nonclinical cases (5) in swine in 2009. (2009 CDC)

2.1.7 *Salmonella* Prevalence Versus Quantified Studies

Usually *Salmonella* contamination is expressed as a prevalence, and very few quantified studies exist, are usually expressed as most probable numbers (MPN). (Davies et al. 2004) This is problematic on several levels. Firstly, prevalences from different sampling schemes and tests may not give comparable results. (Binter et al. 2011) Secondly, both dose and route of exposure contribute to the persistence and establishment of *Salmonella* infection. (Davies et al. 2004) In swine, oral doses of 10^8 CFU have been necessary to reliably achieve infection. (Davies et al. 2004)

2.2 Sources of *Salmonella* Contamination and their Control

The control of *Salmonella* throughout the farm-to-fork continuum has proven to be difficult, especially in primary production. The ecology of *Salmonella* has proven to be remarkably complex, and recontamination occurs easily if proper hygiene measures are not observed.

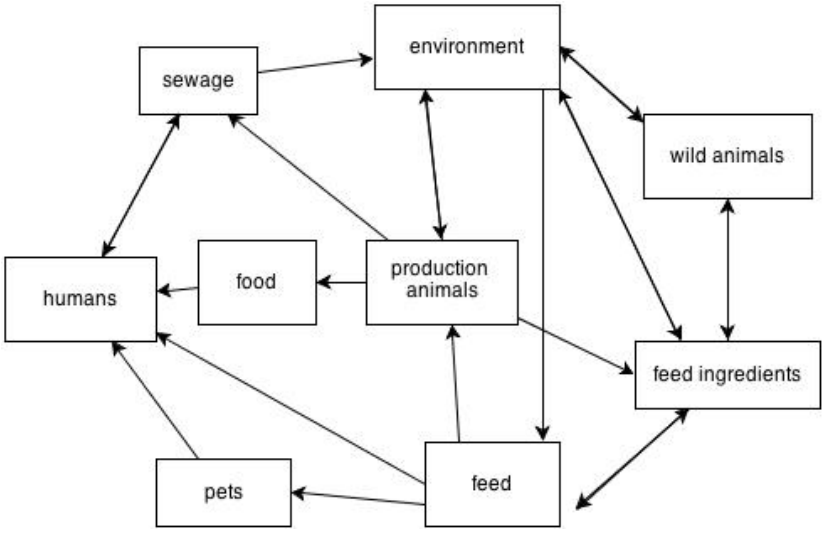

Diagram 1: The complex ecology of *Salmonella*.

2.2.1 *Salmonella* Control on the Farm

On a *Salmonella*-free farm, the entry points for *Salmonella* are through the acquisition of infected swine or *Salmonella*-contaminated feed, contact with rodents and birds and their excreta, or through contact with fomites or vectors such as visitors or trucks.

Salmonellae cause food-related epidemiological outbreaks, and can cause feed-related outbreaks in similar fashion. (Binter et al. 2011) It has been suggested that the role of feed in the epidemiology of *Salmonella* varies with the prevalence of *Salmonella* in the herd. In countries with a high prevalence of *Salmonella*, infected swine are the primary route of infection. (Binter et al. 2011) In countries with a low prevalence of *Salmonella*, feed becomes an important route of transmission and is the

primary method in which novel *Salmonella* strains are introduced onto a farm. (Binter et al. 2011) For example, in Sweden, a two contaminated batches of feed from feed mills infected 78 swine herds and farms. (Wierup and Haggblom 2010) That is why ensuring that swine are fed a *Salmonella*-free diet is one of the cornerstones of pre-harvest *Salmonella* control systems.

Salmonella is extremely difficult to eradicate from farms that are already contaminated. The primary reasons are the environmental hardiness of *Salmonella*, poor efficacy of cleaning and disinfection in the farm environment, and difficulty maintaining biosecurity from rodent, bird and insect vectors. For these reasons, on a *Salmonella*-free farm, a purchasing policy should be instated for *Salmonella*-free swine. (De Busser et al. 2013) Visitors must also change their boots and clothing and caretakers that travel abroad must also test themselves for *Salmonella* so as not to pass on their *Salmonella* infection to the swine.

Vaccination against *Salmonella* is currently not feasible in Europe, because most *Salmonella* surveillance programs use the O-antigen based ELISA which does not distinguish between vaccinated (*Salmonella* Typhimurium live vaccine, Salmopork) and infected swine. (De Busser et al. 2013) Antibiotic use should be limited, as it can easily breed resistance in *Salmonella*.

2.2.2 *Salmonella* Control during Transport and at the Slaughterhouse

Salmonella programs that do not aim at complete eradication of *Salmonella* aim at reducing the number of *Salmonella* organisms through proper hygiene and pig stress management. Stress induces persistent carriers to shed *Salmonella*. Especially at transport and lairage before slaughter, swine are subjected to multiple stressors. *Salmonella* contamination at these points often contaminate the external surface of the pig with *Salmonella* and lead to carcass contamination. Transport causes a great deal of stress to swine during loading and unloading, and can be aggravated with high transport density, long transport durations and routine feed withdrawal. Lairage is needed for swine to recuperate from transport, but fighting between swine during lairage is common. Transport vehicle and lairage cleanliness is thus of utmost

importance. Effective cleaning and disinfection is important, but can be difficult to achieve, especially since disinfection will not be effective if cleaning is done improperly. (De Busser et al. 2013)

Salmonella contamination can also occur during slaughter. It has been suggested that 5–15% of carcass contamination occurs during polishing and 50–90% during evisceration. Scalding water, the splitter machine, and meat inspection (knives) are some of the phases during slaughter that can cross-contaminate carcasses. (De Busser et al. 2013) The thorough examination of slaughterhouse hygiene measures is beyond the scope of this thesis, but one method must be mentioned that has previously been banned in the EU. Carcass decontamination with hot water and acidified sodium chlorite reduce *Salmonella* prevalence on carcasses very effectively. (De Busser et al. 2013) Hot-water decontamination requires major investment costs, but cost-benefit studies have shown it to be less costly than farm-level interventions. (Davies 2004)

2.2.3 Controlling Feed Mill Contamination

In feed operations, feed ingredients are a route for novel strains of *Salmonella* to be introduced onto the premises of feed mills. (Binter et al. 2011) Frequently, animal feed ingredients, especially protein meals derived from animals or plants, are contaminated with *Salmonella*. (Wales et al. 2010) In feed mills that employ decontamination steps for incoming feed ingredients, when *Salmonella* prevalence in incoming feed ingredients is so high that it overwhelms the ability of the decontamination process to remove the *Salmonella*, the feed mill environment may become contaminated. (Wierup and Haggblom 2010)

If a decontamination step is not employed, the microbial quality of the feed depends on the microbial quality of the feed ingredients and the microbial status of the feed production environment. (Binter et al. 2011) Contamination may originate from the feed ingredient, crushing or processing plant, or at the compounding mill. (Wales et al. 2010) Potential points of the recontamination of feeds are during post-decontamination processing and handling at feed mills, transport, storage, delivery to farms and administration. (Crump et al. 2002)

Both feed ingredients and feed should therefore be secured against the entry of pests and their excreta during harvest and storage. Pest control can be difficult when feed ingredients are left to dry in the fields. Silos also fail to protect feed indefinitely.

2.2.4 *Salmonella* Testing

Testing for *Salmonella* is inefficient and costly, as the organism is heterogeneously distributed in clusters in a river of feed, and overall contamination is low. (Davies et al. 2004) This means frequent samples must be taken to test for *Salmonella*. (Binter et al. 2011) A *Salmonella*-negative standard is, moreover, a relative standard, and does not ensure that feed is *Salmonella*-free. (Davies et al. 2004) Detection limits are dependent on feed sampling protocols and the sensitivity of the testing method. (Ibid.) Thus, to use the river analogy, where should the control points be set and what are the ways that *Salmonella* should be sampled at feed mills for maximum efficacy? What should be done to a batch of *Salmonella* positive feed or feed ingredients? How much of the constant river of feed should be decontaminated or discarded?

Binter et al. (2011) have analyzed the rate of *Salmonella* contamination between commodities. They have looked into the reported prevalence of non-processed and processed feeds, finding relatively high prevalences of *Salmonella* in processed feed materials such as processed animal proteins, vegetable protein, and fish meal. Binter et al. (2011) highlight the fact that currently there is a lack of data on the prevalence of *Salmonella* in feed ingredients before they undergo processing, especially from transportation and feed material production lines, because sampling tends to occur later in the feed chain. (Binter et al. 2011)

Feed production and feed mill design influence the number of samples needed for efficient monitoring, and sensitivity for sampling strategies in feed production have not been systematically compared. (Wierup and Haggblom 2010) It has been shown that dust from pelleting can also cause the contamination and is often a better indicator of contamination of a feed mill than mere feed sampling. (Binter et al. 2011,

Torres et al. 2011) A study by Torres et al. (2011) in Spanish feed mills linked air intake for coolers inside feed mills to risk of contamination. Feed mills may also be contaminated by a "house flora" serovar of *Salmonella* that may prove difficult to eradicate. (Binter et al. 2011) There is a general consensus that sampling schemes for feed mills should be developed further.

2.2.5 Decontamination Methods

If a *Salmonella*-negative standard is to be enforced, then a decontamination step must be employed. (Davies et al. 2004) Usually this means heat treatment concurrently with pelleting. Heating must reach 80–85°C for 1 minute, conditions which in practice may prove difficult to achieve. (Binter et al. 2011) Energy costs for heating large volumes of feed are high. (Davies et al. 2004) The heat damages vitamins and nutrients in feed. (Binter et al. 2011) After heat treatment, the feed is also susceptible to subsequent recontamination. (Davies et al. 2004) In a cross-sectional Spanish study, non-pelleted compound feed had eight times the odds of being contaminated than pelleted compound feed. (Torres et al. 2011)

Chemical treatment is also often employed for decontamination, as the effects of chemical treatments can, in theory, keep feed from recontamination during storage. Organic acids and their salts, terpenes and essential oils and formaldehyde can be used, especially conjointly, to gain synergistic effects. Corrosion and reduced palatability as well as the carcinogenesis resulting from formaldehyde limit the use of chemical decontaminants. Chemical treatment, however, can also mask the presence of *Salmonella* by interfering with diagnostics. (Wales et al. 2010)

2.3 The US Feed Industry

With an annual output of 120 million tons of animal feed in 2004, the US animal feed industry is the largest in the world, exporting nearly four billion USD worth of animal feed ingredients. (Sapkota et al. 2007) The international trade of feed is commonplace and far-reaching.

2.3.1 The Global Movement of Feed and Suitable Ingredients for Feed

The structure of the global feed industry and its potential to rapidly spread contaminated animal feed and feed ingredients has been a major cause for concern among epidemiologists. (Crump et al. 2002)

Sapkota et al. (2007) have reviewed animal feed ingredients and their potential impact on human health, primarily relying on data from the Association of Feed Control Officials, which monitors feed use and develops (non-binding) guidelines for the safe use of animal feed. Animal husbandry has driven the industry to adopt feed practices that create the highest yields by consuming feeds that are formulated to increase growth rate and feed-conversion efficiencies. (Ibid.) As the production of swine has intensified, pig farmers have been economically motivated to ever seek out new ways to transform cheap industry waste and by-products into ingredients that can be used in animal feeds. Rendering products and animal waste are an example. (Ibid.) The prices of available feed ingredients in any given place vary, and so consequently do pig diets.

Recently, the US government subsidies on ethanol and biodiesel production has had the consequence that swine may be fed distiller's grains such as dried distiller's grains with solubles (DDGS), or wet distiller's grains (WDG), the co-products of this production process. Potential health hazards for DDGS's have not been investigated in scientific literature, although meat quality issues have been published.

2.3.2 The Structure of Feed Production

In the U.S. domestic market, the structure of feed production and farming is complex. On-farm mixer-feeder operations, where on-site mixing of self-produced rations occurs, are common. Most pig farmers also buy at least some of their feed from outside, commercial operations, depending on the price and need for type of feed. The three types of commercial operations that they source from are feed mills, rendering plants, and protein blenders. Approximately 17,500 feed distributers or feed dealers transport the feed to feeding operations. (Sapkota et al. 2007)

Feed mills refer to plants that combine feed ingredients, including some that are licensed by the FDA to manufacture feed that contain medications such as antibiotics. Feed is mixed for a particular age or species of animal. Feed for different animal species is often mixed at the same mill. (Sapkota et al. 2007) In the event of contamination, several types of animal reservoirs may be affected, including animal units internationally. An estimated 8000 feed mills operate in the US. The largest 85 feed companies operate 1850 mills, producing an annual combined capacity of 154 million tons of feed. (Crump et al. 2002)

Rendering plants process slaughter by-products such as meat scraps and animals unfit for human consumption into animal feed ingredients by grinding, cooking, and pressing. 264 rendering plants exist in the U.S. (Sapkota et al. 2007) Protein blenders are plants that acquire animal and vegetable protein from more than one source or species, and blend, mix, and redistribute them as animal feed. (Sapkota et al. 2007)

2.3.3 Animal By-products

Rendered products are easily and frequently contaminated with *Salmonella* from the intestines of affected animals, and control of visible feces on carcasses continues to be a critical control point in slaughterhouse operations. It is reasonable to assume that serovars associated with poultry, swine or bovines are more likely to contaminate the rendered product made from that animal.

Salmonella prevalence in animal by-products was a popular topic of investigation throughout the 1960's and 1970's. For example, Loken et al. (1968) tested 1395 samples of rendered products from seven plants in the USA and found 17% of their samples to be contaminated. According to Hacking et al. (1978), over a four month period, *Salmonella* was detected in 81% of the meat meal produced in Ontario feed mills.

Results from the FDA Feed Contaminants Program in 2002–2006 and Salmonella Assignment in 2007–2009 indicate that there has been a reduction of *Salmonella* prevalence in animal-derived feed ingredients in the US from 66.1% to

51.3%. (Li et al. 2011) This is still a very high percentage of contamination, even higher than results from Loken et al. in 1968. In another study by Kinley et al. (2010), the prevalence in the US was 8,7% in a study with 150 samples in 2010. That is near the level of prevalence in plant products, which was 11.0 and 10.6 in 2002–2006 and 2007–2009 respectively. (Li et al. 2011) The lack of change in prevalence in plant products suggests that the environmental burden of *Salmonella* is still very high and has not fallen. Improvements in slaughter hygiene and application of HACCP principles have considerably reduced the prevalence of *Salmonella* in rendered animal products.

Overall prevalence of all animal feeds is high in the US. Of 2,058 samples, 257 (12.5%) were positive for Salmonella (2002–2009). (Li et al. 2012) Overall reduction in prevalence has occurred from 18.2% in 2002 to 8.0 in 2009. (Ibid.)

Salmonella from rendered products are often assumed to originate from isolates that have colonized the animal. The serovars isolated by Kinley et al. (2010) suggest that *Salmonella* in rendered protein meals likely comes from recontamination that can occur from the environment, transport, birds, or rodents.

In many countries, *Salmonella* in rendering products is still a very important research topic. In China, a *Salmonella* prevalence of over 13% is found in rendering products. (Han 2000, He & Wang 2009)

Franco et al. (2005) included most probable number (MPN) estimates for a range of rendered animal protein meals for *Salmonella*. In the 197 *Salmonella*-positive samples gathered over a 12 month period, MPN/g values ranged from <0.03 to 1,100, with a mean MPN/g value of 16.3, and median MPN/g value of 0.09. Franco et al. (2005) also serotyped the *Salmonella*, and noted that the 10 most common serovars isolated from rendered animal protein meals do not correspond to serovars that cause most clinical cases in animals or humans. Franco et al. (2005) concluded that there is limited risk in feeding animals rendered protein meals.

2.3.4 Plant-derived products

In Europe, improvements in slaughter hygiene has shifted the attention of the scholarly community from rendering products to grains and vegetable-based feeds,

which are also routinely contaminated with *Salmonella*. (Wierup 2010) In previous studies of non-animal derived feed ingredients, cotton seeds had the highest prevalence of contamination. (Torres et al. 2011) Binter et al. (2011) found soybeans to have the highest prevalence.

2.4 Approaches in Official *Salmonella* Surveillance and Control Systems

Salmonella is an important public health risk. *Salmonella* surveillance and investigations into outbreaks in humans (and animals) are conducted by government public health officials. Due to differences between countries in matters such as climate, industry and governmental structure, and *Salmonella* prevalence in the environment, several approaches have been taken toward the surveillance and control of *Salmonella*. I will briefly introduce the *Salmonella* surveillance and governmental control systems in the USA and Finland as models of pre-harvest and post-harvest control of *Salmonella*.

2.4.1 *Salmonella* Surveillance and Control in Finland: A Model of Pre-Harvest Control

Finland has one of the world's lowest incidences of *Salmonella* infections in its populace. Approximately 2000–3000 cases of human salmonellosis are diagnosed per year. (Huttunen et al. 2006) This equates to 54–65 cases per 100,000 people per year. (Huttunen et al. 2006) Only in 15% of cases – 9 cases per year – is the disease contracted in Finland. (Ranta 2004) A quantitative risk assessment of *Salmonella* in pork production in Finland approximated salmonellosis attributable to pork to be 0–129 cases of salmonellosis in 1999, 40% of which was estimated to be caused by imported pork. (Ranta 2004)

When Finland joined the EU in 1995, Finland was granted "additional guarantees" for *Salmonella*. The additional guarantees are an exception to internal trade policy and free movement of goods within the EU. Finland is allowed to require testing of raw, imported pork, poultry, and beef in the country of origin for *Salmonella*. Sweden and Norway, which run similar *Salmonella* control programs, are exempt from

this requirement. The National *Salmonella* control program was approved by the Commission Decision 94/968/EC. The implementation of the program ensures that the annual incidence of *Salmonella* remains under 1% in swine, poultry and bovines. (Ranta 2004) The Swedish, Finnish and Norwegian models of *Salmonella* control are based on the assumption that all *Salmonella* serovars are equally zoonotic and infectious. (Osterberg et al. 2010)

In an evaluation of the program, the cost of the Finnish *Salmonella* control program for broilers was estimated to be 990,400 euros. (Huttunen et al. 2006) The cost distribution amongst shareholders was: primary production 38%, food industry 68%, and government 2%. (Ibid.) Finland undertook measures to rid the country of all *Salmonella*-positive poultry, swine, and bovines by culling flocks and herds and sanitizing farms, and employing a *Salmonella*-negative feed policy. In the initial phase of the program, the government compensated farmers for following herd culling and sanitization procedures. (Ibid.)

Currently, imported pork accounts for only 8% of Finnish consumption. (Huttunen et al. 2006) If imports were to account for a higher percentage of consumption, salmonellosis would also be more common, because *Salmonella* has been routinely found from products certified to be *Salmonella*-free. Currently 11% of all imported pork fall under the additional guarantees. (Huttunen et al. 2006) Companies importing meat to Finland must no doubt pay a premium for *Salmonella*-free meat and testing abroad. If the additional guarantees would be lifted, the consumption of imported pork would rise.

The additional guarantees do not extend to feed. Before joining the EU, Finnish egg packaging plants, dairies and slaughterhouses formed the Association for the Prevention of Animal Diseases, ETT, to ensure proper feed control in Finland, because it is such an integral part of *Salmonella* control. ETT keeps a list of feed producers that comply with their requirements for the control *Salmonella* in feeds. The Finnish Food Safety Authority Evira also monitors *Salmonella* in feeds and feed mills.

Finnish border control is risk-based and targeted at feed ingredients. One composite sample is taken per 50 tons of feed ingredient. The batch of feed can be released into use only after a *Salmonella*-negative result. If the sample comes back

positive for *Salmonella*, Evira may give permission for decontamination and resampling before release, or deny entry of the feed into Finland.

2.4.2 *Salmonella* Surveillance and Control in the US: A Model of Post-Harvest Control

In the USA, the CDC conducts interstate outbreak investigations. The CDC also runs six surveillance systems, through which the CDC gathers information about *Salmonella* epidemiology in the human population. The CDC monitors the prevalence of *Salmonella* and the number of disease outbreaks, and documents antimicrobial-resistant infections and serovars isolated from humans. Companies have a large role in recalling products in the case of a *Salmonella* outbreak.

Control measures for *Salmonella* in the US currently focus on post-harvest measures such as slaughterhouse hygiene and decontamination measures at slaughter. For over a decade, the US has implemented the final rule on Pathogen Reduction and Hazard Analysis and Critical Control Point (HACCP) Systems, which sets pathogen reduction performance standards for *Salmonella* at slaughterhouses. The US Department of Agriculture Food Safety and Inspection Service (USDA FSIS) conducts testing to verify that these standards are met.

In the US, consumer awareness of *Salmonella* is high. It is probable that efforts to inform consumers of hygienic practices and of the risks of eating uncooked meat has lowered the prevalence of *Salmonella* infections in humans. (Crump et al. 2002)

The US Food and Drug Administration (FDA) is the authority that ensures that feed does not pose a hazard to human health when fed to food-producing animals. Recently, on July 16th, 2013, the FDA issued a new compliance policy guide for feeds. In livestock and horse feeds, serovars that are "capable of causing disease in the animal for which the feed is intended", are banned. Consequently, *Salmonella* Cholerasuis is the only serotype currently banned in swine feed. The existence of other *Salmonella* serovars in feeds will be dealt with on a case-by-case basis. (FDA 2013)

In practice, this change in policy may not bring about significant changes in practical policy enforcement. The previous policy was a *Salmonella*-negative policy for

animal feeds. The *Salmonella*-negative policy, however, was never implemented or enforced. (Crump et al. 2002)

In pet foods, all serovars of *Salmonella* are still considered potentially harmful to human health and pet foods are necessitated to undergo treatment if *Salmonella* is isolated, because of the risk associated with humans directly handling pet food.

2.4.3 Debate on the Causal Relationship Between *Salmonella* Contaminated Swine Feed and Human Salmonellosis

Does *Salmonella*-contaminated swine feed lead to human food-borne illness? The risk to human clinical illness posed by *Salmonella* contaminated feeds has been difficult to assess. (Binter et al. 2011) Quantitative risk assessments of the contribution of contaminated animal feed to human illness have not been published in the US. However, control measures and control programs are being developed on the basis of assumptions of a causal relationship – or the lack of one.

Arguments for the US to Implement a Salmonella-negative Policy

Crump et al. (2002) put forward the hypothesis that non-typhoidal serovars of *Salmonella* contracted from contaminated feed may contaminate carcasses at slaughter and cause foodborne illness in humans and called for a HACCP program to be instituted for the animal feed industry. The central argument was that animal feeds harbor the same serovars of *Salmonella* as people who fall ill, the most important example of which was *Salmonella* Agona. *Salmonella* Agona was a rare serovar in food production, animals and humans before *S.* Agona contaminated Peruvian fish meal was fed to chickens in the 1960s. Now *S.* Agona is one of the serovars commonly isolated from clinically ill humans, and has been estimated to have caused over one million cases of human bacterial illness in the United States. (Crump et al. 2002)

The reasons that human foodborne illness outbreaks have not been traced back to contaminated feed lie in the lack of an integrated system and insufficient surveillance for the detection of the links between feed, food producing animals, and

human illness. There is limited identification of animals and record-keeping on farms, a lack of microbiological evaluation of feeds even when the source of outbreak is traced back to a farm, and surveillance of animal feed is not sufficiently developed or integrated with the surveillance of food production animals and human cases of illnesses. (Crump et al. 2002)

Crump et al. (2002) called for more sampling of animal feeds to develop data which could contribute to the assessment of the impact of animal feed interventions and prove the relationship between contaminated feed and human illness.

Arguments against the US Implementing a Salmonella-negative Policy

Responses have also pointed out the need for a structured survey in the US on the extent of *Salmonella* contamination of animal feed to enable an informed debate on the efficacy and feasibility of enforcing a *Salmonella* negative standard for animal feeds. (Davies et al. 2004) Davies et al. (2004) argue that the (Swedish) model of pre-harvest control may not be feasible to adopt in the United States, because it would be intelligent to employ measures with maximum benefit and minimum cost across the pre-harvest to post-harvest continuum.

Davies et al. (2004) define a ”pre-harvest food safety strategy” to be the modification of farm or farm supplier practices that can reduce the risk of foodborne hazards, and where the risk can be sustained after harvest to the point of consumption. The pre-harvest strategy works well in microbiological agents with suitable, relatively simple, epidemiological characteristics and that are unable to replicate in products, such as bovine spongiform encephalopathy. A pre-harvest strategy also works well in the control of chemical and physical hazards such as dioxins, as well as parasitic hazards. Davies et al. (2004) claims that is not suitable for an organism with a complex ecology. The central argument of Davies et al. (2004) is that at any local intervention, recontamination ”downstream” in the farm-to-fork continuum would render the intervention ineffective.

Farm units in the US are also considerably larger than in Finland or Sweden, where pre-harvest food safety programs are in use. There is considerable contact between animals and the soiled environment, which would need to be addressed first.

(Davies et al. 2004) The Finnish *Salmonella* program requires that restrictive measures be implemented on *Salmonella*-positive farms, *Salmonella*-positive herds be culled and premises cleaned and disinfected thoroughly before repopulation. (Huttunen 2006) This can be an extremely costly process. The Danish model of *Salmonella* control combines pre-harvest and post-harvest measures, but refrains from culling entire herds, and instead focuses on reducing the infection level because "eradication in swine herds is difficult due to the continual nature of the production system". (Wegener et al. 2003)

If a *Salmonella*-negative policy for feed were enforced, it would probably only pertain to the commercial mixing of feed, as is the case in the EU. The mixer-feeder operation has not been subject to the same kind of scrutiny as feed mills, although the size of individual feed mills may be very large. In epidemiological studies in the EU, commercial feeds have been found to counter-intuitively be positively associated with *Salmonella* risk, when compared to unregulated on-farm feeds. It is speculated that this increased risk may be due to pelleting. (Davies et al. 2004)

3 AIMS OF THE STUDY

There is a poor understanding of the relative risk of different feed ingredients and the prevalence, number, and distribution of *Salmonella* serovars in different feed ingredients and raw materials. It is likely that dissemination through feed is more important for some *Salmonella* serovars than others, and that prevalence of *Salmonella* in different substrates could vary. It is unknown what the significance of these differences is for human and animal health.

The aim of this thesis is to examine data from previous research to establish whether there is a greater risk of occurrence of *Salmonella* in certain feed ingredients, and whether sufficient data is available to link specific serovars of *Salmonella* with specific feed ingredients. Information on prevalence and serovars of specific feed ingredients and raw materials, as well as doses (reflected through most probable

numbers, MPN) would be important to find. Also, data on emerging feed ingredients such as distiller's grains with solubles (DDGS) would be highly valuable.

With feed-specific data, feed mills could make better risk assessments based on prevalence and serovars of *Salmonella* in feed ingredients, leading to better testing regimens. Feed mills could also refrain from using a feed ingredient with high risk, or add a decontamination step.

I will also discuss the implications of the results on US and Finnish *Salmonella* control, and identify demand for further investigation.

4 MATERIALS AND METHODS

I conducted a search for academic articles on CAB abstracts, PubMed, and Google Scholar during the summer of 2011 and compiled a feed ingredient database in Microsoft Excel. The feed ingredient database included source information such as the title and year of publication, authors; ingredient data such as the ingredient name and general category; sampling data such as the sampling year and country of origin, and number of samples, *Salmonella* positives, negatives and prevalence; and data on isolated serovars. Other variables such as sampling season, antibiotic resistance, MPN data, whether the article was based on a governmental survey, and other notes were included on a case-by-case basis. I widened the search to also include information from state control program publications (zoonosis reports) from Finland, Sweden, and Norway when it became evident that data in scientific articles was limited.

I had access to online and physical materials at the library at the University of Minnesota, USA and the University of Helsinki, Finland. The primary language of results was English, but results in other languages were not ruled out. Access to foreign-language articles was limited due to the libraries' collections. Search terms included "*Salmonella*", "feed", "ingredients", "swine" and their combinations, but I did not exclude studies on *Salmonella* in other animal feeds, as animal feed ingredients often tend to be the same. I also had access to a list of the ten most common swine feed

ingredients by volume used in the US industry, that I used in my search: corn, soybean meal, wheat middlings, dried distiller's grains, rice by-product (hulls), wheat, rapeseed (canola) meal, corn gluten feed, sorghum, rendered products, sunflower meal, cottonseed meal, cane molasses, and animal fat. All types of investigations that yielded *Salmonella* prevalence in specific feed ingredients were included.

Salmonella prevalences are difficult to compare. Observed prevalence may be biased by **variations in sampling procedures** as well as **limitations in detection methods**. (Binter et al. 2011) I will portray the central information in the feed ingredient database in four tables. I have grouped all the feed ingredients according to their feed ingredient name.

The data in Tables 1–3 is the ratio of positive samples to all samples taken. For example, if Study 1 took 3 samples with a 100% prevalence and Study 2 took 2000 samples and 300 of them were positive, my prevalence would be calculated thus: 303/2003= 10.1%. If a study used another type of sampling method (by gathering composite samples, for example) or prevalence, the study prevalence was used. I am thus comparing samples and prevalences directly, even though sampling protocols and how prevalences are calculated and assessed may vary between studies. Also, *Salmonella* may lend itself to be isolated from some feed ingredients more easily than others.

This leads us to discuss the challenges of feed ingredient categorization. Unfortunately, universal, agreed-upon nomenclature for feed ingredients does not exist. Because most often the name of the ingredient is the only description of the feed ingredient, the database may include ingredients that are called the same, but are actually different products. For example, "meat meal" may refer to poultry derived meat meal and pork derived meat meal.

The opposite may also be true. For example, "soya meal" and "soybean meal" may refer to the same product. However, because of the risk posed by conflating categories, I decided to enter into the database only the ingredient names originally used in the studies.

5 RESULTS

5.1 Evaluation of Sources and Source Data

The literature search yielded 38 studies spanning five decades, from 1961–2011, with studies from Austria, Canada, China, Denmark, Finland, Germany, Iraq, the Netherlands, Norway, Reunion Island, Saudi Arabia, South Africa, Spain, Sweden, Switzerland, Tanzania, the U.S.A., the U.K., and Zimbabwe. The majority of the sources were derived from the U.S.A. and Europe. Since many swine feed ingredients are also used in other animal feeds, the database contains feed ingredients for feeds meant for swine as well as poultry, turkeys, cattle, dairy cows, and fish. The broad scope of my study reflects the dearth of information in this area. I gathered data from across many decades and countries because there is little data available.

Information on *Salmonella* could be found from a variety of sources. None of the articles focused specifically on *Salmonella* in ingredients for swine feed. Limited microbiological surveys are available of animal feed ingredients, and when *Salmonella enterica* is isolated, many isolates are never typed. The serovars listed in the feed ingredient database are mostly derived from different studies than the prevalences. As a general rule, earlier studies aimed at ascertaining prevalences, whereas serovars and antibiotic resistance have been the interest of newer publications.

The main types of publications that contained information on *Salmonella* feed ingredients were: state regulatory program results, *Salmonella* prevalence in rendering products, surveys of *Salmonella* prevalence in feed constituents and feeds to determine risk of transmission, epidemiological investigations into feed mills, *Salmonella* serovar typing to determine the chain of transmission, analyses of microbiological quality of feeds and feed ingredients, seasonal variation of the prevalence of *Salmonella* in feeds, and the antibiotic resistance of *Salmonella* in feeds.

It must be noted that a significant portion of the data on specific feed ingredients has been published at relatively early dates, especially the 1960s–1970s,

when the ecology of *Salmonella* was being investigated. (Al-Hindawi & Taha 1979, Hacking et al. 1978, Isa et al. 1963, Lee et al. 1972, MacKenzie & Bains 1976, Morehouse & Wedman 1961, Moyle 1966) These studies often had very small sample sizes. Data from Northern Europe is voluminous, but zoonosis reports tend to group ingredients by general categories, such as “Other feed of vegetable origin”. (Huttunen et al 2006).

5.2 Feed Ingredient Database Results

Tables 1–3 depict information on animal feed ingredients, plant-derived feed ingredients and miscellaneous feed ingredients, respectively. Blanks in the following tables indicate that the information was not available.

First of all, it must be noted that a great range of feed ingredients of animal-, plant- and miscellaneous origin can become contaminated with *Salmonella.* Inferences cannot be made from the prevalences of specific feed ingredients such as “blood”, “apple waste”, or “rice” in Tables 1–3, because sample numbers are so few (column Total number of samples). Small sample sizes do not give a reliable indication of the prevalence of *Salmonella* in specific feed ingredients. Positive results can only be taken as an indication that there is the possibility that a specific feed ingredient can be contaminated with *Salmonella*.

Large amounts of sampling, on the other hand, has resulted in publication of results in conflated categories, such as the category “Meat and bone meal, fish meal, greaves, bone meal, meat meal, milk products and poultry offal meal” in Table 1. (SVA 2010)

Table 1. Prevalence and Serovars of *Salmonella enterica* in Animal-Derived Feed Ingredients

Feed ingredient	Prevalence %	No. of positive samples	Total no. of samples	Serovars[a] (No. of times isolated)[b]	Reference
Meat and bone meal, beef	100.0	1	1		McChesney et al. 1995
Fish	75.0	3	4		McChesney et al. 1995
Poultry	52.9	9	17	S. Montevideo, S. Newhaw, S. Johannesburg	McChesney et al. 1995
Blood	50.0	3	6	S. Brandenburg (1), S. Livingstone (1)	McChesney et al. 1995
Meat meal	47.6	493	1036	S. Montevideo (103), S. Minnesota (71), S. Eimsbuettel (61), S. Worthington (50), S. Senftenberg (48), S. Anatum (44), S. Tennessee (35), S. Kiambu (31), S. Liverpool (27), S. Zanzibar (25), S. Binza (22), S. Derby (22), S. Thomasville (22), S. Coley park var. 0-14 (20), S. Havana (19), S. Cubana (18), S. Lille (18), S. Livingstone (18), S. Cerro (16), S. Bareilly (15), S. Muenster (13), S. Newington (13), S. Typhimurium (13), S. Concord (12), S. Oranienburg (12), S. Singapore (12), S. Lexington (11), S. Mgulani (11), S. Bredeney (10), S. Drypool (7), S. Infantis (7), S. Kentucky (7), S. Braenderuo (6), S. Barnum (6), S. Corvallis (6), S. Grumpensis (6), S. Pankow (6), S. Sieburg (6), S. Agona (5), S. California (5), S. Muenchen (5), S. Schwarzengrund (5), S. Johannesburg (4), S. Meleagridis (4), S. Orion (4), S. Sandiego (4), S. 21:b- (4), S. Champaign (3), S. Halmstad (3), S. Manila (3), S. Aberdeen (2), S. Adelaide (2), S. Cambridge (2), S. Give (2), S. Hadar (2), S. Illinois (2), S. Javiana (2), S. London (2), S. Menston (2), S. Newport (2), S. Saint Paul (2), S. Vejle (2), S. 21:b,Z40, (2), S. Abortus bovis (1), S. Birmingham (1), S. Blockley (1), S. Bournemouth (1), S. Caracas (1), S. Chester (1), S. Fayed (1), S. Heidelberg (1), S. Java (1), S. Kaapstad (1), S. Kottbus (1), S. Manhattan (1), S. Mission (1), S. Mississippi (1), S.	Hacking et al. 1978, Isa et al. 1963, Williams et al. 1969, Hummel 1976, MacKenzie & Bains 1976, Morehouse & Wedman 1961, Flatscher & Willinger 1981, Nabbut et al. 1982, Durand et al. 1990, Bisping 1993, Kohler 1993, McChesney et al. 1995, Kinley et al. 2010

Table 1. Continued.

Feed ingredient	Prevalence %	No. of positive samples	Total no. of samples	Serovars[a] (No. of times isolated)[b]	Reference
				Okerara (1), S. Orion (1), S. Poona (1), S. Rubislaw (1), S. Stanley (1), S. Souza (1), S. Teddington (1), S. Thompson (1), S. Uganda (1), S. Westhampton (1), S. Yeerongpilly (1), S. 3, 15: Z10- (1)	
Poultry by-products	32.9	49	145	S. California, S. Agona, S. Montevideo, S. Cerro, S. Newhaw	Morehouse & Wedman 1961, McChesney et al. 1995
Meat scraps	31.6	276			Morehouse & Wedman 1961
Meat scraps and bone meal	26.4	86	326		Morehouse & Wedman 1961
Miscellaneous animal protein	22.6	7	31		Morehouse & Wedman 1961
Fish pellets	20.1	53	264		Skovgaard & Nielsen 1972
Fat	20.0	1	5		Morehouse & Wedman 1961
Protein feed supplements	17.3	241	1395	S. Bredeney (73), S. Cerro (33), S. Binza (27), S. Oranienburg (24), S. Senftenberg (12), S. Anatum (9), S. Illinois (8), S. Tennessee (8), S. Alachua (6), S. Halmstead (5), S. Derby (4), S. Kentucky (4), S. Thomasville (4), S. Newington (3), S. Worthington (3), S. California (2), S. Canoga (3), S. 6,7,14:y;1,5 (3), S. Eimsbuettel (2), S. Infantis (2), S. Montevideo (2), S. Sieburg (2), S. Thompson (2), S. St. Paul (2), S. Give (1), S. Minnesota (1), S. Newport (1), S. Schwarzengrund (1)	Loken et al. 1968
Protein	15.6	7	45		Al-Hindawi & Taha 1979
Bone meal	15.4	24	156	S. Worthington (3), S. Newington (2), S. Brandenburg (1), S. Bredeney (1), S. Derby (1), S. Kentucky (1), S. Oranienburg (1), S. Paratyphi B (1), S. Schwarzengrund (1), S. Senftenberg (1)	Morehouse & Wedman 1961, Isa et al. 1963, Durand et al. 1990, McChesney et al. 1995
Tankage	14.6	46	316		Morehouse & Wedman 1961
Meat and bone meal, poultry	14.3	1	7	S. Montevideo (1)	McChesney et al. 1995, Kinley et al. 2010
Animal by-products	13.9	273	1963	S. Senftenberg (1), S. Cerro (1)	Morehouse & Wedman 1961, Allred et al. 1967,

Table 1. Continued.

Feed ingredient	Prevalence %	No. of positive samples	Total no. of samples	Serovars[a] (No. of times isolated)[b]	Reference
					McChesney et al. 1995
Ground scrap	12.9	8	62		Moyle 1966
Pressed cake	12.5	3	24		Moyle 1966
Fish meal	11.8	276	2337	S. Senftenberg (98), S. Tennessee (96), S. Anatum (90), S. Lille (68), S. Havana (67), S. Cerro (7), S. Agona (5), S. Hadar (5), S. Typhimurium (5), S. Infantis (4), S. Kentucky (4), S. New-haw (4), S. Enteritidis (3), S. Heidelberg (3), S. Lexington (3), S. Montevideo (3), S. Ohio (3), S. Binza (2), S. Livingstone (2), S. Mbandaka (2), S. Newington (2), S. Alachua (1), S. Amsterdam (1), S. Bareilly (1), S. Bere (1), S. Berta (1), S. Bredeney (1), S. Gallinarium (1), S. Isangi (1), S. Meleagridis (1), S. San diego (1), S. I 6,7;1.5;2 Efnat (1), S. Schwarzengrund (1), S. Stanley (1)	Morehouse & Wedman 1961, Isa et al. 1963, Allred et al. 1967, Williams et al. 1969, Morris et al. 1970, Lee et al. 1972, Skovgaard & Nielsen 1972, Flatscher & Willinger 1981, Nabbut et al. 1982, Durand et al. 1990, Bisping 1993, Kohler 1993, Veldman et al. 1995, Han 2000, Davis et al. 2003, Nesse et al. 2003, Jones & Richardson 2004, He & Wang 2009, Papadopoulou et al. 2009, Torres et al. 2011
Cracklings	9.4	6	64		Moyle 1966
Poultry meal	8.8	7	80		Hofacre et al. 2001, Kinley et al. 2010)
Other protein products (e.g. fish meal)	8.7	2	23		Harris et al. 1997
Blended meal	5.0	3	63	S. Arkansas, S. Livingstone, S. Rotenberg, S Tennessee, S Brandenburg	Hofacre et al. 2001
Herring meal	5.0	3	60	S. Montevideo (3), S. Agona (1), S. Anatum (1), S. Liverpool (1),S. Schwarzengrund (1), S. Tilburg (1)	Skovgaard & Nielsen 1972
Meat and bone meal	3.9	713	18425	S. Senftenberg (138), S. Montevideo (108), S. Anatum (83), S. Tennessee (66), S. Binza (48), S. Mbandaka (45), S. Typhimurium (42), S. Livingstone (31), S. Oranienburg (31), S. Cubana (29), S. Clifton (29), S. Reading (18), S. Bredeney (14), S. Eimsbuettel (11), S. Infantis (11), S. 4,12:d:- (10), S. Minnesota (10), S. Give (8), S. Ruiru (8), S. Cerro (8), S. Dublin (7), S. Thompson (6), S. Kentucky (6), S. Newington (6), S. Alachua (5), S. Havana (5), S.	Skovgaard & Nielsen 1972, Chambers 1977, Nabbut et al. 1982, Cox et al. 1983, Durand et al. 1990, McChesney et al. 1995, Veldman et al. 1995, Han 2000, Hofacre et al. 2001, Jones & Richardson 2004, He & Wang 2009, Papadopoulou et al. 2009, Hofshagen et al. 2010, Kinley et al. 2010

Table 1. Continued.

Feed ingredient	Prevalence %	No. of positive samples	Total no. of samples	Serovars[a] (No. of times isolated)[b]	Reference
				Heidelberg (4), S. Hadar (4), S. Enteritidis-danysz (2), S. Enteritidis (2), S. Pretoria (2), S. Rideau (2), S. Mobeni (2), S. Raus (1), S. Rissen (1), S. Agona (1), S. Amsterdam (1), S. Bareilly (1), S. Lille (1), S. Ohio (1), S. I 6,7;1.5;2 Efnat (1), S. Arkansas (1), S. Rotenberg (1), S Brandenburg (1), S. Uganda (1), S. Johannesburg (1), S. Zanzibar (1), S. Meleagridis (1), S. Pullorum (1), S. Dublin (1), S. Nigeria (1)	
Livers	3.8	1	26		Morehouse & Wedman 1961
Blood meal	2.5	70	2848	S. Clifton (29), S. Singapore (12), S. Newington (6), S. Anatum (5), S. Cerro (5), S. Senftenberg (3), S. Mobeni (2), S. Pretoria (2), S. Rideau (2), S. Worthington (2), S. Lille (1), S. Montevideo (1), S. New Brunswick (1), S. Nigeria (1), S. Bredeney (1), S. Dublin (1), S. Ohio (1), S. Oranienburg (1), S. Raus (1), S. Rissen (1), S. Tennessee (1), S. Typhimurium (1), S. Zanzibar (1)	Morehouse & Wedman 1961, Isa et al. 1963, Moyle 1966, MacKenzie & Bains 1976, Chambers 1977, Kinley et al. 2010
Other feed of animal origin	2.3	15	639	S. Infantis (3), S. Anatum (1),S. Isangi (1), S. Orion (1), S. Typhimurium (1)	Huttunen et al. 2006
Feed fish and fish refuse	1.0	1	99		Huttunen et al. 2006
Meat and meat-bone powder	0.5	21	4599	S. Livingstone (6), S. Agona (1), S. Muenster (1), S. Adelaide (1), S. Anatum (1), S. Cerro (1), S. Infantis (1), S. Kentucky (1), S. Liverpool (1), S. Montevideo (1), S. Senftenberg (1), S. Tennessee (1)	Huttunen et al. 2006
Fish powder	0.4	12	2903		Al-Hindawi & Taha 1979, Huttunen et al. 2006)
Meat and bone meal, fish meal, greaves, bone meal, meat meal, milk products, and poultry offal meal	0.3	3	959		SVA 2010
Blood (pork)	0.0	0	2		McChesney et al. 1995
Blood plasma, dried	0.0	0	1		McChesney et al. 1995

Table 1. Continued.

Feed ingredient	Prevalence %	No. of positive samples	Total no. of samples	Serovars[a] (No. of times isolated)[b]	Reference
Blood, dried	0.0	0	5		Al-Hindawi & Taha 1979
Bone powder	0.0	0	10		Al-Hindawi & Taha 1979
Denatured skimmed milk powder	0.0	0	1		Bisping 1993
Fats/oils	0.0	0	16		Harris et al. 1997
Feather/blood	0.0	0	1		McChesney et al. 1995
Fish oil	0.0	0	8		Hofshagen et al. 2010
Milk by-products	0.0	0	7		Isa et al. 1963
Milk products	0.0	0	277		Huttunen et al. 2006
Milk, whey	0.0	0	14		Harris et al. 1997
Pig concentrate pellets (meat and bone meal, meat meal, dried milk and other)	0.0	0	8		Lee et al. 1972
Poultry manure, heat sterilized	0.0	0	254		Durand et al. 1990
Whey	0.0	0	1		Jones & Richardson 2004
Whey and dried buttermilk	0.0	0	6		Morehouse & Wedman 1961

[a]Serovars presented from investigations in which *Salmonella enterica* was serotyped.
[b]Serovars without numbers in parentheses represent the most common isolates.

In Table 1, meat meal can be seen to have a very high prevalence of contamination: 47.6%. An explanation for this may be that most of the sources were either published over two decades ago, when animal by-product processing hygiene was not what it is today. However, both blood meal and meat meal are processed products, and yet notable differences can be seen in their prevalences. Blood meal (2.5%) and other blood-related ingredients can be seen to have contamination levels much lower than that of meat meal.

Out of this pool of studies, only Franco et al. (2005) has published quantified data (MPN-estimates) on feed ingredients. The study evaluates the MPN estimates in rendering products, but they used very general feed ingredient categories and thus their results are of limited use in this investigation.

Fish and fish by-products can also be seen to have a relatively high amount of contamination. Out of all animal products, milk and milk products such as whey have low prevalence.

Data is unfortunately not available to classify rendering products in Table 1 by animal species. I have tried to keep as many specific ingredients in the database as possible as a reference. The more specific and less processed a raw ingredient, the more of value the results for estimating prevalence and risks associated with unprocessed feed ingredients. Unfortunately, most studies did not indicate at what point the sample was taken and whether the feed ingredients had undergone processing. Thus it is difficult to tell from Tables 1–3, which ingredients have been processed and which are raw ingredients. This would have been important information that could help determine the origin of the contamination.

Of course, we are also interested in the level of contamination of feed ingredients that have undergone processing, as swine are regularly fed industry by-products. For example, in plant-derived meals (Table 2), all oilseed meals refer to processed products. Oilseed meal is what remains after crushing to remove the oil. Extraction methods may vary, and some may predispose the product to contamination.

Table 2. Prevalence and Serovars of *Salmonella enterica* in Plant-Derived Feed Ingredients

Feed ingredient	Prevalence %	No. of positive samples	Total no. of samples	Serovars[a] (No. of times isolated)[b]	Reference
Rapeseed meal	100.0	1	1		McChesney et al. 1995
Rolled grain	100.0				Kidd et al. 2002
Safflower meal	100.0	2	2		FDA Survey Determines Salmonella Contamination
Rapeseed meal (Canola meal)	66.7				Kidd et al. 2002
Beet pulp, pelleted	50.0				Kidd et al. 2002
Corn, flaked	50.0				Kidd et al. 2002
Cottonseed meal	50.0	5	10		McChesney et al. 1995, Jones & Richardson 2004
Corn/barley mix	40.0				Kidd et al. 2002
Corn distillers' grains	28.6				Kidd et al. 2002
Corn grits	26.7	4	15	S. Hadar (4), S. Tennessee (4), S. Havana (3), S. Cerro (2), S. Mbandaka (2), S. Senftenberg (2), S. Agona (1), S. Alachua (1), S. Amsterdam (1), S. Anatum (3), S. Bareilly (1), S. Infantis (1), S. Lille (1), S. Livingstone (1), S. Ohio (1), S. I 6,7;1.5;2 Efnat (1)	Veldman et al. 1995
Silage	24.0	42	175	S. Cubana (17), S. Havana (17), S. Lexington (6), S. Senftenberg (6), S. Newport (3), S. Typhimurium (3), S. Anatum (1), S. Cerro (1), S Oranienburg (1)	Davis et al. 2003, Dargatz et al. 2005
Screenings	20.0	3	15	S. New-Brunswick (1), S. Oranienburg (1), S. Rubislaw(6)	Hacking et al. 1978
Cotton seeds	17.2	58			Davis et al. 2003, Papadopoulou et al. 2009, Torres et al. 2011
Soy	14.6		337	S. Senftenberg (73), S. Tennessee (49), S. Agona (44), S. Havana (42), S. Mbandaka (34), S. Cerro (1)	Wierup & Haggblom 2010

Table 2. Continued.

Feed ingredient	Prevalence %	No. of positive samples	Total no. of samples	Serovars[a] (No. of times isolated)[b]	Reference
Biscuit waste	14.0	14	100	S. Havana (3), S. Singapore (3), S. Typhimurium (3), S. Tennessee (2), S. Bornum (1), S. Eimsbuettel (1), S. Infantis (1)	MacKenzie & Bains 1976
Protein meals altogether (vegetable)	10.3	131	5250		Wierup & Haggblom 2010
Rape	10.0				Wierup & Haggblom 2010
Soybean meal (47%)	10.0	1	10		Jones & Richardson 2004
Vegetable feed ingredients	9.7	7	72		Skovgaard & Nielsen 1972
Peanut meal	9.6	5	52	S. Cubana (2), S. Newington (1), S. Tennessee	MacKenzie & Bains 1976, McChesney et al. 1995
Sunflower meal	7.9	57	718	S. Bornum (5), S. Cubana (3), S. Eimsbuettel (3), S. Lille (3), S. Havana (1), S. Orion (1), S. Senftenberg (2), S. Singapore (1)	MacKenzie & Bains 1976, McChesney et al. 1995, Torres et al. 2011
Soybean meal	5.6	567	10120	S. Infantis (13), S. Singapore (5), S. Braenderuo (3), S. Kentucky (2), S. Agona (1), S. Albany (1), S. Anatum (1), S. Havana (1), S. Léopoldville (1), S. Newington (1), S. Oranienburg (1), S. Tennessee (1), S. group C1 (6, 7; y) (1), S. Senftenberg (1), S. Enteritidis, S. Cubana, S. Senftenberg, S. Montevideo	Isa et al. 1963, MacKenzie & Bains 1976, Hacking et al. 1978, Bauduret 1990, Bisping 1993, Kohler 1993, McChesney et al. 1995, Harris et al. 1997, Wierup & Haggblom 2010, Torres et al. 2011
Sunflower seed derived	4.4	4	90		Hofshagen et al. 2010
Wheat middlings	4.2	1	24		Jones & Richardson 2004
Wheat bran	4.1	147	3585		Torres et al. 2011
Corn, dry	4.0	7	175	S Cubana (17), S. Havana (17), S Lexington (6), S Senftenberg (6), S Newport (3), S Typhimurium (3), S Anatum (1), S Oranienburg (1)	Dargatz et al. 2005
Soya bean derived	3.4	106	3096		Hofshagen et al. 2010
Bran meal	3.3	5	150	S. Lille (2), S. Senftenberg (2), S. Typhimurium (1)	MacKenzie & Bains 1976
Oilseeds	3.3	1	30	S. Braenderup (1)	Kohler 1993
Rice	3.3	1	30		Al-Hindawi & Taha 1979

Table 2. Continued.

Feed ingredient	Prevalence %	No. of positive samples	Total no. of samples	Serovars[a] (No. of times isolated)[b]	Reference
Wheat	2.8	5	181	S. Typhimurium (48), S. Agona (16), S. Newport (15), S. Agama (14), S. 4, 12:d:- (14)	MacKenzie & Bains 1976, Al-Hindawi & Taha 1979, Jones & Richardson 2004, Papadopoulou et al. 2009
Wheat flour	2.3	86	3739		Torres et al. 2011
Oilseed meals	2.3	60	2628		Allred et al. 1967
Hay	1.7	6	360	S. Cubana (17), S. Havana (17), S. Lexington (6), S. Senftenberg (6), S. Newport (3), S. Typhimurium (3), S. Anatum (1), S Oranienburg (1)	Dargatz et al. 2005
Tapioca	1.7	1	58	S. Hadar (4), S. Anatum (3), S. Havana (3), S. Cerro (2), S. Mbandaka (2), S. Senftenberg (2), S. Agona (1), S. Alachua (1), S. Amsterdam (1), S. Bareilly (1), S. Lille (1), S. Livingstone (1), S. Infantis (1), S. Ohio (1), S. Tennessee (4), S. I 6,7;1.5;2 Efnat (1)	Veldman et al. 1995
Other feed of vegetable origin	1.5	3	198		Huttunen et al. 2006
Alfalfa (lucerne)	1.0	1	100	S. Eimsbuettel (1), S. Typhimurium (1)	MacKenzie & Bains 1976, Davis et al. 2003
Oil plant seeds and by-products of these (except sunflower seeds)	1.0	288	29910	S. Tennessee (105), S. Mbandaka (53), S. Cubana (9), S. California (4), S. Rissen (2), S. Sambre (2), S. Agona (1), S. Altona (1), S. Amsterdam (1), S. Lexington (1), S. Meleagridis (1), S. Typhimurium (1), S. Urbana (1), S. Wien (1)	Huttunen et al. 2006
Sorghum	1.0	1	100	S. Senftenberg (1)	MacKenzie & Bains 1976
Palm kernel, rape seed, soya bean, sunflower seed, groundnut and linseed	0.9	32	3481	S. Livingstone (1), S. Newsport (1), S. Velje (1)	SVA 2010
Barley	0.8	223	29632	S. Typhimurium (9), S. Mbandaka (4), S. Derby (3), S. Enteritidis (3), S. Rissen (3), S. havana (1), S. Infantis (1), S. Senftenberg (1)	Papadopoulou et al. 2009
Palm kernel	0.8			S. Senftenberg (114), S. Ruiri (45), S. Tennessee (43), S. Kentucky (42), S. Mbandaka (36)	Papadopoulou et al. 2009, Wierup & Haggblom 2010

Table 2. Continued.

Feed ingredient	Prevalence %	No. of positive samples	Total no. of samples	Serovars[a] (No. of times isolated)[b]	Reference
Cereal grains	0.7	21	2981	S. Anatum (2)	Allred et al. 1967, Al-Hindawi & Taha 1979, Kohler 1993, Harris et al. 1997, Sauli et al. 2005
Corn, high moisture	0.6	1	180		Dargatz et al. 2005
Sow nuts (barley, wheat)	0.6	1	162		Skovgaard & Nielsen 1972
Corn	0.4	258	62040	S. Schwarzengrund (54,) S. Agona (35), S. Kedougou (20), S. Tennessee (16), S. Havanna (12), S. Rauh (1), S. Eimsbuettel (1)	MacKenzie & Bains 1976, Kohler 1993, Jones & Richardson 2004, Papadopoulou et al. 2009, Wierup & Haggblom 2010, Torres et al. 2011
Seeds of grains and products and by-products of these	0.3	16	5996	S. Livingstone (10), S. Typhimurium (2), S. Agona (1), S. Infantis (1), S. Kottbus (1), S. Muenchen (1)	Huttunen et al. 2006
Oil plant seeds and products of these	0.2	4	2280		Huttunen et al. 2006
Barley derived	0.0	0	1		Hofshagen et al. 2010
Brewer's grains	0.0	0	3		Jones & Richardson 2004
Cereal grain derived (not specific)	0.0	0	14		Hofshagen et al. 2010
Cereal grains, mostly oats, corn, wheat, rice	0.0	0	80		Sauli et al. 2005
Corn germ meal	0.0	0	1		McChesney et al. 1995
Corn gluten, pelleted	0.0				Kidd et al. 2002
Corn, ground	0.0	0	15		Hacking et al. 1978
Corn, including corn derived	0.0	0	156		Hofshagen et al. 2010
Feed material of cereal grain origin	0.0	0	77	S. Mbandaka (5), S. Cubana (4), S. Agona (2), S. Infantis (2), S. Ruiru (2), S. Senftenberg (2), S. Glostrup (1), S. Havana (1), S. Isangi (1), S. Livingstone (2), S. Newport (1), S. Ohio (1), S. Stratford (1), S. Tennessee (1), S. Typhimurium (1)	SVA 2010
Forage crop meals	0.0	0	6		Isa et al. 1963
Grass and hay powders	0.0	0	507		Huttunen et al. 2006
Legume seeds and similar	0.0	0	152		Hofshagen et al. 2010

Table 2. Continued.

Feed ingredient	Prevalence %	No. of positive samples	Total no. of samples	Serovars[a] (No. of times isolated)[b]	Reference
products					
Linseed expeller meal	0.0	0	1		Bisping 1993
Linseed meal	0.0	0	1		McChesney et al. 1995
Malt	0.0	0	30		Al-Hindawi & Taha 1979
Oat derived	0.0	0	5		Hofshagen et al. 2010
Oil seed or fruit origin	0.0	0	34		Hofshagen et al. 2010
Other feeds of vegetable origin	0.0	0	340		Huttunen et al. 2006
Rapeseed	0.0				Kidd et al. 2002
Rapeseed (Canola, pelleted)	0.0				Kidd et al. 2002
Rapeseed (environmental)	0.0	0	545		SVA 2010
Rapeseed derived	0.0	0	245		Hofshagen et al. 2010
Rice shell	0.0	0	30		Al-Hindawi & Taha 1979
Shorts, bran, middlings	0.0	0	6		Isa et al. 1963
Soy pak	0.0				Kidd et al. 2002
Soya meal	0.0	0	52		Sauli et al. 2005
Soybean hulls	0.0	0	5		Jones & Richardson 2004
Soybeans	0.0	0	30		Al-Hindawi & Taha 1979
Sugar and starch industry products	0.0	0	5938		Huttunen et al. 2006
Tubers, roots and similar products	0.0	0	24		Hofshagen et al. 2010
Wheat derived	0.0	0	91		Hofshagen et al. 2010
Apple waste		1		S. Typhimurium (1)	Davis et al. 2003
Beet pulp		2		S. Meleagridis (1), S. Typhimurium (1)	Davis et al. 2003
Corn silage		1		S. Typhimurium (1)	Davis et al. 2003
Corn, crushed		3		S. Cerro (1), S. Typhimurium (1)	Davis et al. 2003
Cottonseed/corn pulp mix		1		S. Cerro (1)	Davis et al. 2003

Table 2. Continued.

Feed ingredient	Prevalence %	No. of positive samples	Total no. of samples	Serovars[a] (No. of times isolated)[b]	Reference
Grain mill waste		3		S. Cerro (2), S. Typhimurium (1)	Davis et al. 2003
Linseed		385		S. Mbandaka (202), S. Tennessee (61), S. 4:b:- (22), S. Montevideo (12), S. Braenderup (11)	Papadopoulou et al. 2009
Pea flour		1		S. Braenderup (1)	Davis et al. 2003
Rapemeal		2433		S. Tennessee (771), S. Mbandaka (399,) S. Agona (291), S. Ealing (170), S. Ruiru (85)	Papadopoulou et al. 2009
Rice bran		242		S. Senftenberg (32), S. Cubana (24), S. Tennessee (17), S. Agona (16), S. Kentucky (16)	Papadopoulou et al. 2009
Soya		2935		S. Mbandaka (626), S. Senftenberg (243), S. Agona (196), S. 4:12:d:- (165), S. Binza (162)	Papadopoulou et al. 2009
Straw		1		S. Cerro (1)	Davis et al. 2003
Sunflower		406		S. Mbandaka (47), S. Senftenberg (42), S. Tennessee (35), S. Agona (28), S. Cubana (19)	Papadopoulou et al. 2009
Unspecified vegetable		37		S. Montevideo (13), S. Ohio (11), S. Typhimurium (3), S. Senftenberg (1), S. Give (1)	Papadopoulou et al. 2009

[a]Serovars presented from investigations in which *Salmonella enterica* was serotyped.
[b]Serovars without numbers in parentheses represent the most common isolates.

If feed ingredients with fewer than 100 samples are ignored, out of all non-animal-derived feed ingredients, cottonseeds have the highest prevalence of contamination, 17.2% (Table 2). Table 2 also shows that oilseeds and their by-products are consistently more likely to be contaminated than other plant-based products such as grains. *Salmonella* prevalence in distiller's grains, a relatively new by-product from commercial ethanol production that is used in pig production, ranged from 0–28%. It was not indicated whether these were DDGS or WDG.

In addition to traditionally researched animal- and plant-based feed ingredients, *Salmonella* can contaminate feed supplements (Table 3) such as direct-fed organisms like feedstuff yeast (4.1%) and minerals such as calcium carbonate (4.2%).

It is important to note that negative results with small sample sizes, such as in the case of the feed ingredients "urea" and "limestone" in Table 3, do not mean that the specific feed ingredient cannot be, or is not usually, contaminated with *Salmonella*. Results can, however, give us an indication of which serovars of *Salmonella* can survive in these feed ingredients.

Table 3. Prevalence and Serovars of *Salmonella enterica* in Miscellaneous Feed Ingredients Such as Minerals, Vitamins, and Direct-Fed Organisms

Feed ingredient	Prevalence %	No. of positive samples	Total no. of samples	Serovars[a] (No. of times isolated)[b]	Reference
Swine supplements	50.0	2	4		Morehouse & Wedman 1961
Raw materials	26.1	36	138		Skovgaard & Nielsen 1972
Feed concentrate	7.8	6	77		He & Wang 2009
Other	7.1	1	14		Moyle 1966
Calcium carbonate ($CaCo_3$)	4.2	3	72	S. Livingstone	Al-Hindawi & Taha 1979, Nabbut et al. 1982
Feedstuff yeast	4.1	3	64	S. Albany (1), S. Anatum (1), S. Senftenberg (1)	Kohler 1993
Yeast	3.3	1	30		Al-Hindawi & Taha 1979
Other (grower-finisher premix)	2.2	1	45		Harris et al. 1997
Pulverized shell	2.0	2	100	S. Cubana (1), S. Senftenberg (1)	MacKenzie & Bains 1976
Others	1.7	288	1694		Torres et al. 2011
Brewer's yeast concentrate	0.0	0	1		Bisping 1993
Limestone	0.0	0	1		Jones & Richardson 2004
Nuts (Pig nuts)	0.0	0	1		Lee et al. 1972
Protein concentrate	0.0	0	2		Bisping 1993
Urea	0.0	0	1		Isa et al. 1963
Cocoa		103		S. Tennessee (11), S. Ibadan (8), S. Malstatt (4), S. Morningside (4), S. Stockholm (3)	Papadopoulou et al. 2009
Protein concentrate		53		S. Mbandaka (6), S. Senftenberg (5), S. Kentucky (4), S. Anatum (3), S. Livingstone (3)	Papadopoulou et al. 2009

[a]Serovars presented from investigations in which *Salmonella enterica* was serotyped.
[b]Serovars without numbers in parentheses represent the most common isolates.

5.3 *Salmonella* Serovars in Feed Ingredients

The ability of serovars to survive in animal-derived products, cereal grains, and oilseeds is shown in Table 4.

Table 4. *Salmonella enterica* serovars isolated from animal feeds by category

Serovar	Animal protein	Cereals	Oilseeds
Aberdeen	2		
Abortus bovis	1		
Adelaide	3		
Agama		14	
Agona	13	70	561
Alachua	10		
Albany			1
Altona			1
Amsterdam			1
Anatum	167	3	1
Banana	1		
Bandenburg	1		
Bareilly	16		
Bere	1		
Berta	1		
Binza	99		162
Birmingham	1		
Blockley	2		
Bornum	6	1	5
Bournemouth	1		
Braenderup	6		15
Brandenburg	1		
Bredeney	113		
California	8		4
Cambridge	2		
Canoga	3		
Caracas	1		
Cerro	69	3	2
Champaign	3		
Chester	1		
Clifton	58		
Coleypark var 0-14	20		

Table 4. Continued.

Serovar	Animal protein	Cereals	Oilseeds
Concord	12		
Corvallis	6		
Cubana	37	45	34
Derby	28	3	
Drypool	7		
Dublin	2		
Ealing			170
Eimsbuettel	63	2	3
enterica subsp. *enterica*	5		
Enteritidis	5	3	1
Enteritidis-danysz	2		
Fayed	1		
Gallinarium	1		
Give	11		
Glostrup		1	
Grumpensis	7		
Hadar	3		
Halmstad	3		
Halmstead	5		
Havana	84	34	44
Heidelberg	8		
Illinois	10		
Infantis	16	5	13
Isangi	2	1	
Java	1		
Javiana	2		
Johannesburg	6		
Kaapstad	1		
Kedougou		20	
Kentucky	24	16	44
Kiambu	31		
Kottbus	1	1	
Leopoldville			1
Lexington	14	6	1
Lille	86	2	3
Liverpool	29		
Livingstone	9	12	1
London	2		
Manhattan	1		
Manila	3		
Mbandaka	43	9	1397
Meleagridis	7		1
Menston	2		

Table 4. Continued.

Serovar	Animal protein	Cereals	Oilseeds
Mgulani	11		
Minnesota	82		
Mission	1		
Mississippi	1		
Mobeni	4		
Montevideo	206		13
Muenchen	5	1	
Muenster	14		
Newbrunswick	1		1
Newhaw	6		
Newington	32		2
Newsport	3	19	1
Nigeria	2		
Ohio	3	1	
Okerara	1		
Oranienburg	50	1	2
Orion	6		1
Pankow	6		
Paratyphi B	1		
Poona	1		
Pretoria	4		
Pullorum	1		
Raus	2	1	
Reading	1		
Rideau	4		
Rissen	2	3	2
Rubislaw	1		6
Ruiru		2	130
Saint paul	4		
Sambre			2
San diego	5		
Schwarzengrund	9	54	
Senftenberg	245	44	476
Sieburg	8		
Singapore	24	3	6
Souza	1		
Species	1		
Stanley	2		
Stratford		1	
Teddington	1		
Tennessee	185	36	1066
Thomasville	26		
Thompson	3		

Table 4. Continued.

Serovar	Animal protein	Cereals	Oilseeds
Tilburg	1		
Typhimurium	45	70	1
Uganda	2		
Urbana			1
Vejle	2		1
Westhampton	1		
Wien			1
Worthington	60		
Yeerongpilly	1		
Zanzibar	27		
4:12:d:-	165		
4:b:-	22		

Based on Table 4, *Salmonella* serovars Mbandaka, Tennessee, Agona, Senftenberg, Ealing, Binza and Ruiru were isolated especially frequently from oilseed ingredients. Out of these seven, serovars Senftenberg, Agona and Tennessee were also isolated from a range of cereal ingredients.

Serovars Havana, Kentucky and Cubana were isolated from many different feed ingredients.

Serovars Schwarzengrund, Kedougou, Newport, Agama, Livingstone may be grain-linked serotypes, as they were mainly isolated from cereal grains. *Salmonella* Derby, an important serotyped linked to illness in Swine, was isolated 3 times from grains, and may also be a grain-linked serotype.

Most serovars were only isolated from animal protein feed ingredients and not from grains or oilseeds or other feed ingredients.

Of the serovars that frequently cause salmonellosis in humans, *S.* Typhimurium is common in grains (70 isolates). Typhimurium was also isolated from a variety of different types of feed ingredients: cereal grains such as corn, bran, barley, wheat; meat, fish, and blood meals; silage, alphalpha, hay, apple waste, vegetables and beet pulp. *S.* Heidelberg was only isolated from meat in this data pool. *S.* Enteritidis was isolated from animal-derived meals including fish meal, as well as plant-derived feed ingredients including soybean meal, and barley. Soybean meal is a processed product. There is not enough data to draw further conclusions. In Table 4, *S.* Montevideo can be

seen to be present frequently in rendered poultry meat meal, oilseeds such as linseed and soybean meal, but not in grains. *S.* Agona is common in many types of feeds. Information was not found on emerging serotypes such as Javiana and 4,[5],12:i:-. There is not enough data on the serovar Worthington.

S. Cholerasuis, which causes generalized disease in swine, was not isolated from feed ingredients or feeds in any of the studies. *S.* Cholerasuis has not been isolated from feeds. (Harris et al. 1997) It remains to be seen whether feeds are a part of the ecology of *S.* Cholerasuis.

5.4 *Salmonella* Prevalence in Feed Ingredient Categories by Region

The level of contamination of the environment with *Salmonella* varies with geographical location. Figure 1 gives *Salmonella* prevalence per feed ingredient category by region (USA, Nordic Countries and Other countries). In the USA, prevalence is rather high in almost all feed ingredient categories and indicates a high environmental burden of *Salmonella*, ranging from 1.7% in grains to 23.3% in rendered products across the entire 1961–2011 time period.

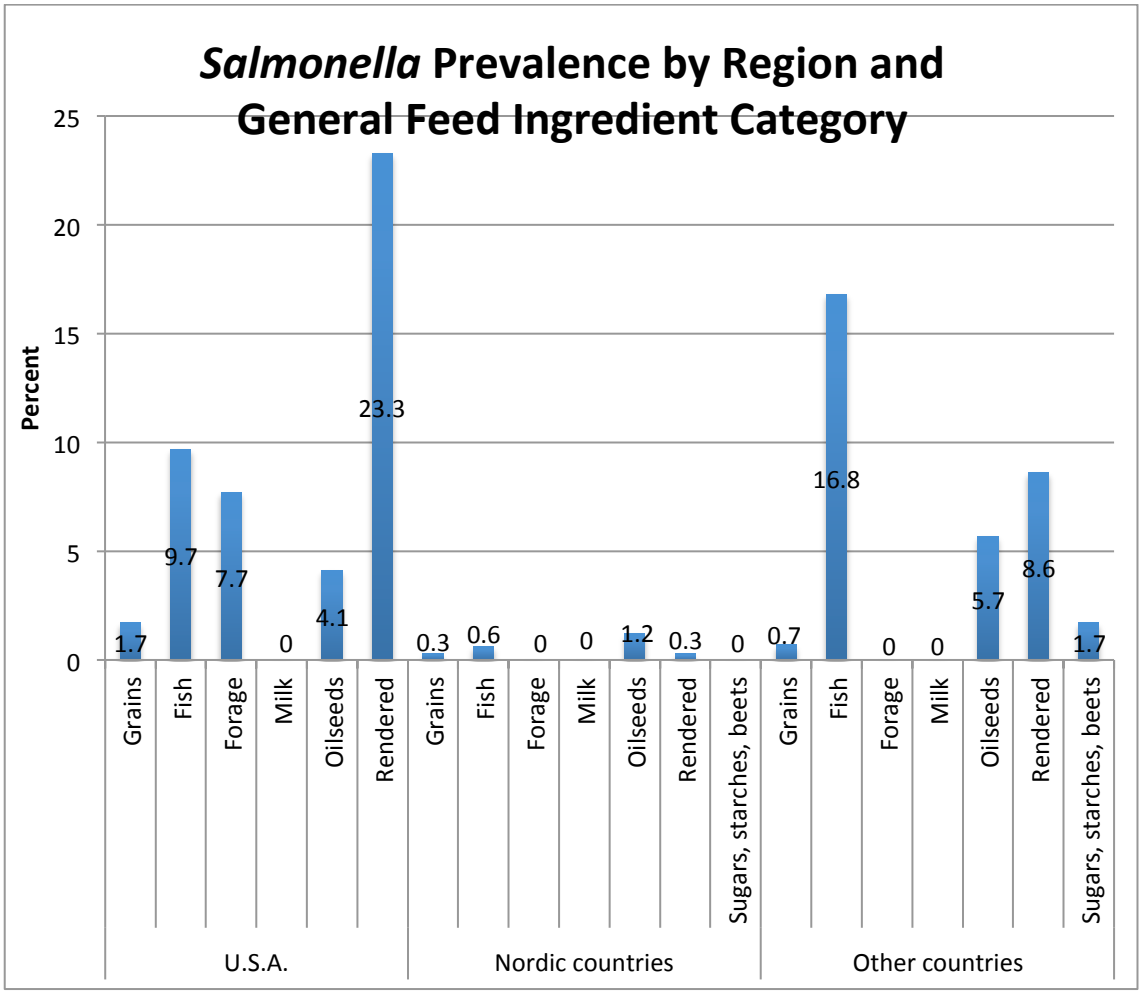

Figure 1. *Salmonella* prevalence by region and general feed ingredient category

From Figure 1, one can also see that in the Nordic countries, oilseeds (plant-based protein meals) are the most important risk ingredient.

Not only is *Salmonella* prevalence lower in the Nordic countries than in other countries, but *Salmonella* testing is far more comprehensive (Figures 2 and 3).

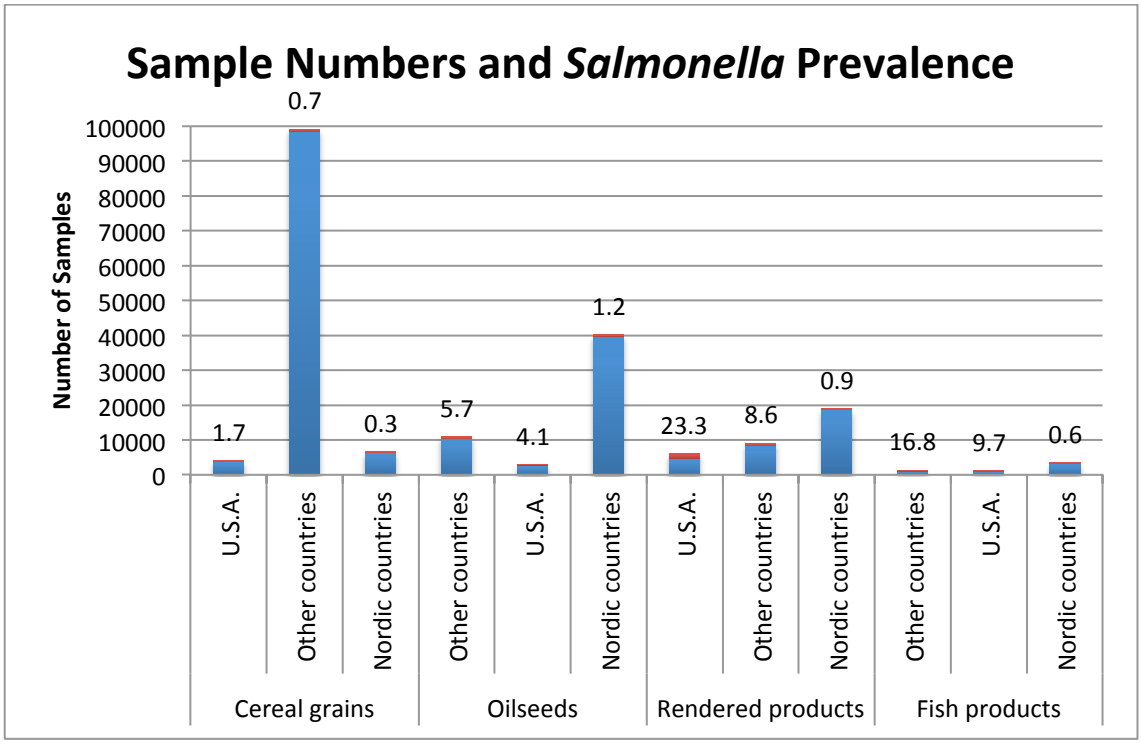

Figure 2. Number of Samples and prevalence of *Salmonella* by region and general feed ingredient category – Cereal grains, oilseeds, rendered products, fish products

Testing has concentrated on rendered products, fish products, oilseeds, and cereal grains (Figure 2). Across all feed ingredients, rendered products are most likely to be contaminated by *Salmonella*.

Sugars, starches and beets, forage crops, and milk products have been tested less frequently (Figure 3).

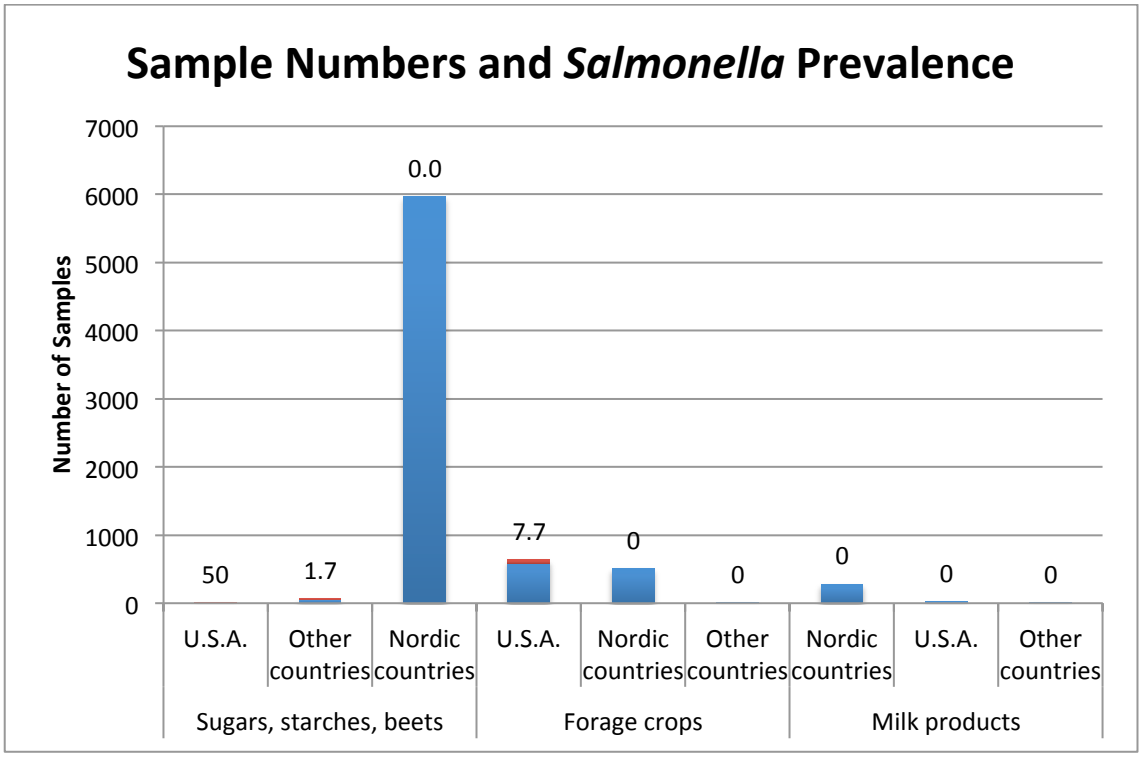

Figure 3. Number of Samples and prevalence of *Salmonella* by region and general feed ingredient category – Sugars, starches, beets; forage crops, milk products

Results from only a few samples have been published from countries other than the Nordic countries. In the Nordic countries, *Salmonella* has not been isolated from these types of feed.

Forage crop contamination is low, 0% in Finland, but 7.7% in the US. The prevalence of *Salmonella* in cereal grains is low, under 1.7% in all countries. Utilizing milk products in animal feeds has not been investigated outside the Nordic countries. In the Nordic countries their utilization does not seem to pose a problem, as prevalence in milk products was 0%.

6 DISCUSSION

Information on prevalence and serovars in feed ingredients is sparse compared to the large volumes of feed that are produced and shipped around the world. Much of the data on specific feed ingredients has been published by investigations with few

sample numbers, many over a decade ago. Data from governmental monitoring programs may be voluminous, but tend to group ingredients by general categories and leave data on specific feed ingredients unpublished.

There is great variation in the number of samples taken between different types of investigations. Epidemiological investigations into feed mills, such as by Hacking et al. (1978), may give a falsely high prevalence of *Salmonella*, as the *Salmonella* contamination spreads throughout the feed mill. Samples from individual feed mills will also be much fewer than from national monitoring programs.

State regulative programs generate large amounts of industry-driven data on *Salmonella* prevalence. (Hofshagen et al. 2011, Huttunen et al. 2006, SVA 2010, Torres et al. 2011). *Salmonella* prevalence in the Nordic countries are exceptionally low, and thus these prevalences cannot be taken to indicate the level of prevalences in other geographic locations. Finland, Sweden and Denmark have a HACCP in place for animal feeds and zero tolerance policy for all serovars of *Salmonella*. *Salmonella* testing is extensive and most samples are negative. For example, in the case of Finland, all consignments of feed entering Finland must also be *Salmonella*-negative and have undergone a treatment step before transportation. Although the prevalence of *Salmonella* in feeds is higher than that of feed produced in Finland, it is still lower than in countries where *Salmonella* negativity for feeds is not a requirement. The prevalence of *Salmonella* in Nordic programs may actually reflect the amount of recontamination that occurs after a decontamination step is taken.

It would be beneficial if food safety authorities and industry representatives that monitor *Salmonella* prevalence were to release more detailed data on specific feed ingredients. In future investigations, *Salmonella* should also be isolated from the raw feed ingredient, allowing for differentiation between the level of contamination of the raw feed ingredient and contamination during processing.

The data analyzed reflects the fact that Salmonella can be isolated from many different feed ingredients. Data on individual feed ingredients must be interpreted cautiously, as sample numbers were few. Out of animal feed ingredients, meat meal is the most likely to be contaminated, and blood least contaminated. Of plant-derived feed ingredients, oilseeds are more frequently contaminated than cereal grains.

Miscellaneous feed ingredients were also shown to harbor low prevalences of Salmonella.

Differences in Salmonella prevalence in feed ingredients may be attributed to multiple factors. The ecology and epidemiology of Salmonella is complex. The burden of disease in pest and wildlife populations, environmental contamination, how well the feed ingredient has been shielded from contamination, and decontamination methods applied to the ingredient all contribute to the prevalence of *Salmonella* in an ingredient. Overall *Salmonella* contamination of the environment and populations of carriers vary widely by location, and thus I analyzed *Salmonella* prevalence by geographical areas (US, Northern Europe, other countries) in addition to by ingredient.

In addition, *Salmonella* is not uniformly distributed within feed. The ability of any given Salmonella serovar to survive in any given feed ingredient may vary. Because of the variables involved, it is difficult at this point to make quantitative risk assessments of specific feed ingredients without further testing.

Rendered products and fish have traditionally been seen as the riskiest feed ingredient for *Salmonella*. However, as the prevalence of *Salmonella* in rendered products fell with improvements in slaughterhouse hygiene, the importance of *Salmonella* contamination via other feed ingredients such as oilseeds and cereal grains became evident.

Rendering products are still the most important of general feed ingredient categories that contributes to Salmonella contamination in feeds in countries that have not implemented pre-harvest salmonella programs, such as the US (23,3%), and other countries (8,6%), as shown in Figure 1. Although HACCP systems are implemented in slaughterhouses and animal by-product production, recent studies on the prevalence of *Salmonella* in rendering products in the US have delivered conflicting results. (Kinley et al 2010, Li et al 2011)

Salmonella serovars vary widely in animal by-products. In fact, most serovars were only isolated from animal protein feed ingredients and not from grains or oilseeds or other feed ingredients. This may be due to the fact that animal-derived feed ingredients have been investigated more due to perceived risk. It may also be that some serovars are adapted to survival in animals rather than in feeds or the environment. One such serovar may be *S.* Cholerasuis.

Plant protein ingredients also have relatively high levels of contamination. Plant protein is the riskiest feed ingredient in countries that implement pre-harvest control programs. Serovar Mbandaka, in particular, is common in oilseeds. (Papadopoulou et al. 2009) In 2005, serovar Mbandaka was one of the main isolates from swine (5.2%), but was not in the top 10 serovars that caused clinical cases. It is possible that Mbandaka may have lowered virulence in swine. Tennessee is also a common serovar in feed ingredients of plant origin that does not significantly cause clinical illness in swine. Furthermore, Mbandaka and Tennessee are not among the 20 most important serovars in human illnesses in 2009 on the CDC list, despite their high prevalence in feeds.

Several of the serovars were common in many different feed ingredients, namely Agona, Cubana, Havana, Kentucky, Senftenberg, and Tennessee. Of these, serovar Agona causes a significant amount of human illness.

The most common serovars in oilseeds were not commonly isolated from animal by-products; only serovar Binza out of serovars Mbandaka, Ealing, Binza and Ruiru was also isolated from animal by-products. *Salmonella* Ealing was only found in rape meal. Salmonella Ealing did not cause any clinical infections in animals in 2009. (CDC 2009) This indicates that, at least on the basis of this data, it does not seem common for oilseed-associated serovars to infect swine.

Serovars isolated frequently from grains were Typhimurium, Schwarzengrund, Kedougou, Newport, Agama, and Livingstone. The fact that *S.* Typhimurium is common in grains is unsurprising, as *S.* Typhimurium causes typhoid-like symptoms in mice. *S.* Typhimurium isolation numbers may largely reflect the burden of disease in rodent vectors that come into contact with these feed ingredients, and the hardiness of *S.* Typhimurium. Davies & Wales (2013) have also noted that even though protein ingredients may be perceived to be of higher risk, the risk posed by cereals should be addressed, because it may involve serovars of great public health importance. There is a definite need for investigation into the virulence of these above mentioned serovars.

There is also a need for comprehensive testing of feed ingredients in countries that do not have pre-harvest *Salmonella* programs. If the US is to advance pre-harvest measures of contamination control on farms or feed mills, investigation especially into prevalences and serovars in forage crops, milk by-products, sugars, starches and beets

should be undertaken. Data from relatively new industry by-products such as Distiller's grains was also sparse and warrants scientific inquiry.

Pre-harvest control programs have been implemented based on the premise that all *Salmonella* serovars are potentially zoonotic. Finland, Sweden, and Norway have *Salmonella* programs that strive to destroy all *Salmonella* serovars in feed ingredients before the feed is mixed and taken to the farm. Pre-harvest *Salmonella* programs require the environmental contamination of *Salmonella* be low. The post-harvest approach later in the food chain in the US means that the microbiological status of the feed is dependent on the microbiological status of feed ingredients. The level of contamination in other feed ingredients is relatively high in the US, indicating wide environmental contamination. Because it is so high, it seems reasonable to assume that discontinuing the use of the highest prevalence products – animal by-products – in feed will raise the price of feed, but may not cause a significant decrease in cases of human salmonellosis. This assessment is supported by the fact that serotypes in animal by-products have been shown to differ from the most common serotypes that cause clinical illness in humans. (Franco et al. 2005)

The U.S. Food and Drug Administration Compliance Policy Guide (CPG) section 690.800 "*Salmonella* in Food for Animals" details a new policy that focuses on host-specific serovars, "the strains that are capable of causing disease in the animal for which the feed is intended". (FDA 2013) The CPG lists *Salmonella* Cholerasuis as the only *Salmonella* serovar that will prompt seizure or decontamination of swine feed. It effectively allows zoonotic *Salmonella* serovars that cause gastroenteritis in both swine and humans to exist in swine feed in the US. In practice, the CPG may not warrant any testing, because *Salmonella* Cholerasuis has not been isolated from feed.

On the basis of the criteria for the capability of causing disease in the animal for which the feed is intended, *Salmonella* Typhimurium should, in my opinion, be on the list *Salmonella* serovars to be banned from feeds. It is pathogenic in both swine and humans and frequently isolated from a range of feeds and feed ingredients.

The CPG also relies on the assumption that *Salmonella* serovars cannot be passed on through swine feed to swine and then on to humans. Without quantitative risk assessments, it is true that there is not enough data to prove the link between the transfer of *Salmonella* from feed ingredients to feeds, from feeds to swine, and from

pork to human illness. However, swine feed commonly contains many of the serovars that cause infection in humans. (Li et al. 2011)

Finnish feed mills have already invested in suitable decontamination equipment and are able to handle feed decontamination adequately. Thus there is no great benefit in switching to serovar-specific models of risk assessment at this juncture. For the Finnish model, taking a serovar-specific approach would mean that after sampling, isolation and typing of a serovar, consignments with low-pathogenic serovars could potentially be allowed to proceed to feed mills and farms. One such possible serotype on the basis of the data reviewed is *S.* Mbandaka. Studies on the pathogenicity and transmission of such serotypes should naturally be undertaken first.

The objective scientific basis for risk assessments help us make increasingly more informed decisions as we find out more about the epidemiology of pathogens. Although it is beyond the scope of my paper, I would be naïve not mention the process of policy formation and the political agendas behind scientific publications on *Salmonella* control, including cost-benefit analyses. The interests of the consumers, the public sector, and especially the feed and production animal industries have had a large effect on the policies of both the US and Finnish governmental *Salmonella* control programs.

There are many reasons why I think that pre-harvest *Salmonella* programs have not been and will not be adopted widely, and why Finland and Sweden have had such success implementing *Salmonella* control even before entry into the EU.

Finland is the northernmost country in the EU. Due to frigid winter temperatures, swine must be housed indoors throughout the year. Building and feed costs make Finland one of the most expensive countries in which to raise swine, and pork production is largely dependent on subsidies. The additional guarantees for *Salmonella* effectively functions as a trade barrier between the countries that implement *Salmonella* programs and the rest of the European Union. Any products that enter the Finnish market and any feeds sold to Finnish farms must be tested for *Salmonella* in the country of origin and can be returned to the country of origin at the sellers' expense if found contaminated. This favors local production.

I would argue that public health care, with costs mostly borne by the state, has greatly contributed the state's eagerness to undertake public health interventions,

including investing in food safety control. In Finland, during the initial stages of the program, farmers received state compensation. After its establishment, the formidable costs of the program were shouldered mainly by industry. Thus the success of the Finnish *Salmonella* control program, I believe, is due to the interests of the domestic industry coinciding with the interests of the state and the public. The industry benefited from the erection of a trade barrier, and the state and the public from a lowered incidence of *Salmonella* in the country.

In the USA, where the industry strives to keep pork production competitive on the international market, agricultural advances and industrialization have been embraced without reserve. The US/multinational industry has demonstrated opposition to governmental oversight of their operations, such as governmental surveillance and control, especially when it is not in their monetary interest. As things stand, industry has successfully lobbied to sculpt policy to their advantage.

The food industry has an ethical obligation to lower the incidence of disease-producing agents in its products. (Davies et al. 2004) However, ethical obligations such as animal health and welfare, and indeed human health, when not directly linked to monetary gains, often take a back seat to more pressing financial issues. Cost-benefit analyses of illnesses also cannot take into account the suffering of people inflicted with preventable diseases that could have been controlled through regulation. Food pathogen outbreaks are of significant national and international concern, and pressure from consumers can be a powerful motivator for both the public and private sectors to work toward ensuring the safety of food and maintaining consumers' and the public's trust.

7 CONCLUSIONS

In conclusion, *Samonella enterica* is a common pathogen that is able to contaminate most feed ingredients. *Salmonella* prevalence and serovars vary between feed ingredients. Differences in serovar survival in different substrates and infectivity of serovars in feed have not been thoroughly investigated. The compiled database

shows a lack of a systematic evaluation of the prevalence and serovars of *Salmonella* in swine feed ingredients, especially in raw, unprocessed materials, and emerging feed ingredients such as distiller's grains with solubles. Unpublished information may be available through *Salmonella* control programs. Quantified studies of *Salmonella* in specific feed ingredients (MPN-studies) have not been undertaken.

Generalizations can be made of *Salmonella* prevalence in feed ingredients. Rendered products tend to have the highest prevalence of *Salmonella* in countries that do not implement pre-harvest *Salmonella* control programs. Out of animal-derived products, blood and milk by-products may be least prone to contamination. Of plant-derived feed ingredients, oilseeds are more frequently contaminated than cereal grains, but cereal grains were frequently contaminated by the serovar *S.* Typhimurium.

Although connections could not be made between specific feed ingredients and specific *Salmonella* serovars, differences between *Salmonella* serovars could be noted in the distribution of their presence in general feed ingredient categories. Several possible oilseed-associated, grain-associated, and general-type serovars were identified. Serovars that cause salmonellosis in humans were also found in swine feeds. *Salmonella* Cholerasuis was not isolated from animal feeds ingredients.

With regard to *Salmonella* serovar-specific risk-assessment, the recently issued United States FDA compliance policy guide does not address zoonotic serovars that cause gastroenteritis in animals and humans. It is possible that if the risk of *Salmonella* Cholerasuis, the only serovar currently banned from feed, is seen as minimal, swine feed testing will not be required. At least *Salmonella* Typhimurium should be on the list *Salmonella* serovars that pose a risk for animal and human health in swine feed.

Since the Nordic countries have already invested significantly in pre-harvest feed safety, there is no great benefit to converting to serovar-specific models of risk assessment at this juncture, when it has not been confirmed that certain *Salmonella* serovars harbored in feeds may not cause illness in swine and humans.

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